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DEVELOPMENT OF AN IMPROVED METHOD FOR PRODUCTION OF TORSION-TUBE SPRINGS FOR TRACKED VEHICLES (U)

FINAL REPORT

U.S. ARMY TANK-AUTOMOTIVE COMMAND
CONTRACT DAAE07-73-C-0235

MARCH 1975

by

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U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

FINAL TECHNICAL REPORT

under

CONTRACT DAAE07-73-C-0235

on

DEVELOPMENT OF AN IMPROVED METHOD FOR PRODUCTION OF TORSION-TUBE SPRINGS FOR TRACKED VEHICLES

for

U.S. ARMY TANK-AUTOMOTIVE COMMAND
ARMOR AND COMPONENTS DIVISION

by

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SUMMARY

The objectives of this manufacturing-development program were to determine methods capable of producing torsion-tube springs that have potential for reducing manufacturing cost with no sacrifice in quality and use of the selected method(s) to fabricate torsion-tube springs for evaluation and test by U.S. Army Tank Automotive Command.

Four extrusion process -- cold extrusion, hydrostatic extrusion, warm extrusion and thick-film hydrostatic extrusion (HYDRAFILM process) -- were reviewed and analyzed during Phase I with respect to their technical and economic capabilities and limitations. The HYDRAFILM extrusion process was selected for the Phase-II effort because it has the advantages of both warm and hydrostatic extrusion -- elevated temperatures to reduce extrusion pressures and a continuous and effective lubricant film to lower pressures even further and to give excellent as-extruded surface finishes.

The Phase-II effort included (1) the HYDRAFILM extrusion of torsion-tube blanks and machining them into torsion-tube springs for test and evaluation and (2) estimation of fabrication costs for torsion tube springs made by use of this technique. The results of the extrusion trials demonstrated that the HYDRAFILM extrusion process can produce a net or near net internal configuration. This capability reduces the machining time and cost of the finish machining operations. The circularity of the as-extruded internal surfaces ranged from 0.001 to 0.003-inch (0.003 to 0.008-cm). The roughness of the internal surfaces ranged from 60 to 100 microinches (1.5 to 2.5-μm); the typical roughness being about 100 microinches (2.5-μm). This was higher than the target value [70 microinches (1.75-μm)]. Better protection of the billet against oxidation during heating may give better as-extruded surface finishes.

The results of the cost analysis predict that use of HYDRAFILM extrusion plus machining could decrease production costs by as much as 25 percent. This potential cost reduction results from starting with a

lower cost material (bar stock instead of cold drawn tubing) and minimizing the amount of machining needed to obtain the finished torsion tube spring.

Extrusion techniques developed during the Phase-II trials demonstrated the feasibility of applying thermo-mechanical processing (TMP) techniques to torsion-tube blank manufacture. Data in the open literature indicate that TMP improves fatigue properties. We believe that this potential merits further investigation.

CONCLUSIONS

Use of the warm HYDRAFILM extrusion techniques developed on this program may lower the cost to produce 4340 steel torsion tube springs as much as 25 percent. This potential for cost reduction is the result of starting with a lower cost material (bar stock instead of drawn tubing) and minimizing the amount of machining needed to obtain the part shape.

The results of the experimental trials demonstrated that the HYDRAFILM extrusion process can provide as-extruded parts that will meet the circularity requirements of the final product. The roughness of the internal surfaces was slightly higher [100 microinch (2.5 μm) average] than the target [70 microinches (1.75 μm)]. The demonstrated potential to form the internal transition during the extrusion operation deletes the need for a difficult internal profile machining operation.

Modification of the tooling design to include a straightening die should provide an as-extruded product that will meet the part straightness requirements. The potential for extruding a "straight" torsion tube blank plus the demonstrated ability to separate the extruded product from the butt as a part of the extrusion cycle opens the door for the application of thermo-mechanical processing techniques to torsion-tube blanks. It is believed that application of TMP could improve the fatigue properties of the torsion tubes.

RECOMMENDATIONS

Battelle believes that the potential for improving the fatigue properties of 4340 steel torsion tubes by application of TMP extrusion techniques merits further investigation. Existing HYDRAFILM extrusion tooling and the 4340 steel extrusion preforms left over from this program could be readily utilized for such a program. Evaluation of TMP parameters such as extrusion temperature and quench rate should be evaluated by tensile and fatigue testing.

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FINAL REPORT

on

DEVELOPMENT OF MANUFACTURING PROCESS FOR PRODUCTION OF TORSION-TUBE SPRINGS FOR TRACKED VEHICLES

to

U.S. ARMY TANK AUTOMOTIVE COMMAND
ARMOR, MATERIAL AND COMPONENTS DIVISION

by

G. A. Gegel and A. L. Hoffmanner

Contract No. DAAE07-73-C-0235

Period Covered: June 6, 1973 to March 15, 1975

INTRODUCTION

Suspension systems based on torsion springs have been used on tracked military vehicles for a number of years. In 1968, Battelle's Columbus Laboratories completed a program for the U.S. Army Tank Automotive Command (USATACOM) aimed at improving the manufacturing methods for torsion-bar suspension springs[(1)*]. The results of this program demonstrated that warm precision upsetting followed by cold spline rolling provides an improved product at costs competitive with machining and broaching procedures. The new fabrication procedure was not adopted at that time, partly because the suspension system being developed for the next generation tank (XM1) was to be substantially different (hydro-pneumatic).

During the past few years, torsion spring suspension systems have been modified to include the tube-over-bar design. This suspension design allows greater vertical movement of the track wheels.

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*References listed at end of the report.

The torsion bars are currently manufactured from AISI 8660 steel and the torsion tubes from aircraft quality AISI 4340 steel. The fabrication method currently used to produce the torsion tubes is the machining of either bored bar stock or seamless tubing. Depending on the configuration of the starting material, up to 80 percent of the original stock is machined away. Thus, a considerable quantity of expensive ($0.50 per pound) alloy steel is reduced to low-value ($0.02 to $0.04 per pound) scrap. In addition, machining does nothing to enhance the metallurgical quality of the material. Many times, the end product is inferior to the starting material because benefits imparted during prior fabrication (such as grain flow) are removed during machining.

Program Objectives

The purpose of this manufacturing-development program was to determine the most desirable process for mass production of torsion-tube suspension springs with respect to unit cost, production rate, product functional characteristics, and product durability and reliability.

The specific objectives of this two-phase program were:

Phase I

(1) Determine manufacturing methods capable of producing torsion tubes that have potential for reducing manufacturing cost with no sacrifice in quality of the end item.

(2) Review the torsion-tube drawings (Ordnance Corps. Drawing No. DTA163468) and associated specifications to identify specified tolerances and surface finishes in excess of those which can easily be maintained by the candidate fabrication processes.

(3) Selection of fabrication method to be used for Phase II experimental trials. Criteria considered

included potential for reduced fabrication cost, and ability to form a near net component having surface finish of 125 microinches (3.1μm).

Phase II

(1) Design and fabricate the tooling necessary to form up to 20 torsion tubes by the manufacturing procedure deemed most promising as a result of the Phase I studies.

(2) Fabrication of up to 20 torsion tubes for test by U.S. Army Tank Automotive Command.

(3) Make a cost estimate for yearly production quantities of 1000, 5000, 10,000, 20,000, and 30,000 parts.

PHASE I - PROCESS SELECTION

The Phase I effort for this program included:

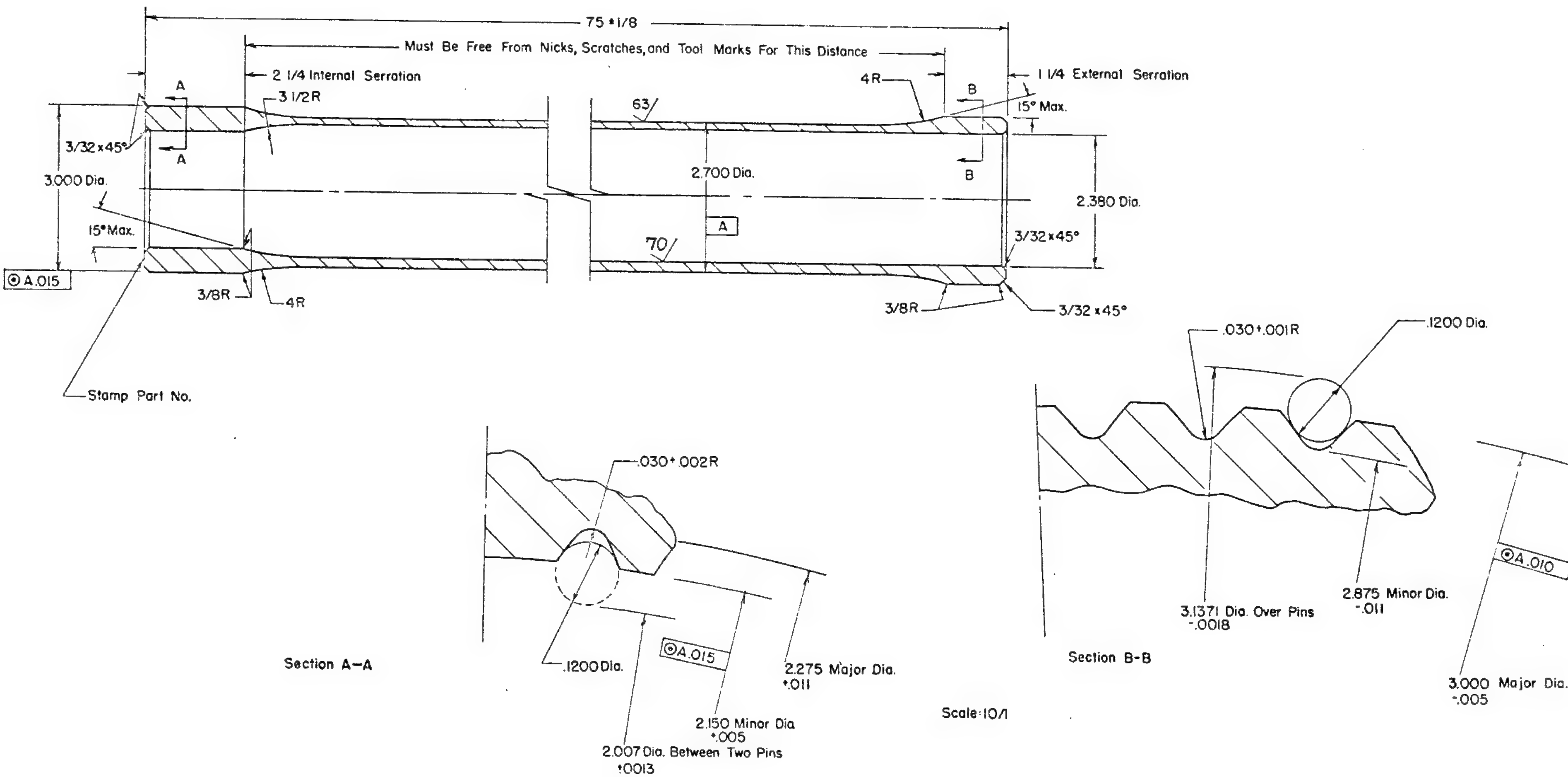
(1) A review of processing technology to determine the methods capable of producing tube-like components having close dimensional tolerances and excellent surface finishes.

(2) A thorough analysis of the torsion tube drawings and associated specifications to identify specified tolerances and surface finishes in excess of those which can easily be maintained by the candidate fabrication processes.

(3) Preparation of a draft processing procedure based on the selected process to include a listing of deviations from current specifications required to allow fabrication in a reasonable manner.

Review of Process Technology

Extrusion processes are ideally suited for the fabrication of tubular components such as the torsion tube spring shown in Figure 1. Use of a close-tolerance extrusion process would (1) minimize the volume



Ref. Ordnance Corp Drawing D TA163468
Dated 1/30/67, Rev. A Dated 12/2/71

Note:
Maximum Permissible Bow, 1/8
Maintain Wall Thickness, .160 ±.010

FIGURE 1. TORSION-TUBE SUSPENSION SPRING FOR TRACKED VEHICLES

of metal to be removed by machining, especially if the internal configuration can be made to net or near net dimensions, and (2) deliver maximum metallurgical integrity.

There are four basic extrusion processes which may be considered for the manufacture of steel tubular components to close dimensional tolerances and having excellent as-fabricated surface finishes:

(1) Cold extrusion

(2) Hydrostatic extrusion

(3) Warm extrusion

(4) Thick-film hydrostatic extrusion--HYDRAFILM process*.

Both of the cold-forming methods--cold extrusion and hydrostatic extrusion--are processes that fabricate parts to close dimensional tolerances. Typical dimensional tolerances on a diameter for cold extrusion would be ± 0.001-inch (± 0.025 - millimeter) for small parts and ± 0.010-inch (± 0.254 - millimeter) for large parts[(2)]. The largest parts commercially produced by conventional cold extrusion weigh about 15 pounds (6.8 - kilograms) and have diameters up to about 8 inches (20.3 cm).

Hydrostatic extrusion has nearly all the advantages of cold extrusion plus the capability of fabricating longer parts and the advantage of lower extrusion pressures. The lower extrusion pressures result because of decreased frictional losses. The pressurized hydrostatic fluid surrounding the billet minimizes contact of the billet with the tooling and also acts as part of the lubrication system.

A practical design limit for hydrostatic extrusion containers, at the present time, is a fluid pressure of 250,000 psi (1725 MPa). An extrusion pressure of this magnitude would give a reduction ratio capability of about 6:1 for cold extrusion of 4340 steel tubing. A 3300-ton (33-MN) extrusion press would be needed to cold extrude the torsion tube component considered in this program.

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*Battelle's designation for thick-film hydrostatic extrusion process; Canadian Patent Serial Number 149,103 to be issued in 1975; Patent applied for in United States.

Warm extrusion at temperatures up to about 700 F (349 C) can be accomplished with the conventional hydrostatic extrusion process. Use of billet temperatures greater than 700 F (349 C) is extremely difficult, if not impossible, because of fluid stability problems. Yet, to be most effective, warm extrusion of hard steel alloys, (AISI 4340 and 8660) requires heating to temperatures above 1300 F (704 C).

Increasing the deformation temperature to the 1400 to 1600 F (760 to 871 C) range decreases the extrusion pressures required considerably. For 4340 steel extruded at a ratio of 6:1, the extrusion pressure is decreased about 36 percent by increasing the extrusion temperature to 1500 F (815 C). However, there are foreseeable difficulties in applying conventional warm extrusion technology to the fabrication of torsion tubes. The problem is maintaining a continuous and effective lubricant film over long lengths. In conventional warm extrusion, the lubricant film thins as extrusion progresses allowing the billet to upset and rub against the extrusion container wall and mandrel. Excessive friction losses result and limit the amount of reduction achievable.

Battelle's HYDRAFILM process combines the advantages of warm extrusion and hydrostatic extrusion--elevated temperatures to reduce extrusion pressures and a continuous and effective lubricant film to lower pressures even further and to attain excellent as-extruded surface finishes. The key features of this process are (1) the use of a minimum quantity of hydrostatic fluid and (2) the capability to accomplish hydrostatic extrusion at billet temperatures up to 1700 F (926 C). The results of several industrially sponsored studies conducted at Battelle have demonstrated the capability of this process to fabricate tubing with as-extruded surface finishes of 10 to 15 microinches (0.25 to 0.38 μm). Conventionally hot-extruded steel tubing normally has a surface finish no better than 150 to 200 microinch (2.5 to 5.0 μm).

Review of Economic Factors

The costs associated with the manufacture of an end item or product may be put into the following categories:

(1) Input material costs

(2) Machining costs

(3) Fabrication costs.

A comparison of the operational steps required to produce torsion-tube springs by machining from either a solid bar or drawn tubing and by warm HYDRAFILM extrusion practices is shown in Table 1. The same basic operations must be accomplished whether one is machining the part from bar stock or from drawn tubing. Although less material is lost to scrap when tubing is used, the value lost to scrap is nearly the same.

The sequence given for the warm HYDRAFILM extrusion process assumes that very little ID machining will need be accomplished. Although the volume of scrap generated is essentially the same as for machining from drawn tubing, the value lost to scrap is lower because the input material cost is much lower.

Fewer machining operations will be required for the part produced by warm HYDRAFILM extrusion and less value will be lost to scrap. Therefore, warm HYDRAFILM extrusion combined with finish machining appears to have a greater potential for cost reduction than the other processes considered.

Review of Torsion Tube Specifications

In order to produce the tubes with little or no machining on the inside diameter, the inside surface of the tubes will remain as-extruded except for the area to be splined. To use tubes with an as-extruded ID, it may prove necessary to modify the surface-finish requirement [35 microinches (0.8 μm) is now specified in Drawing No. DTA163468, Rev. A, dated December 2, 1971]. In the as-extruded condition, the ID may have a slightly rougher surface finish. Exact microinch values were determined as part of this study.

TABLE 1. SEQUENCE OF OPERATIONS FOR FABRICATING TORSION-TUBE SPRINGS BY TWO ALTERNATIVE PROCESSES

	Machining from Bar	Machining from Drawn Tube	Warm HYDRAFILM Extrusion
	Receive and inspect 3-1/8-inch (79.4-millimeber) diameter bar	Receive and inspect 3-inch (76.2-millimeter) OD x 2-inch (50.8-millimeter) ID tubing	Receive and inspect 6-inch (152.4-millimeter) diameter bar
	Straighten if needed	Straighten if needed	--
	Cut to length (saw)	Cut to length (saw)	Cut to length (saw) Heat billets to 1550 F (843 C) Forge preform Reheat to 1550 F (843 C)
			Extrude full length [82 inches (208.3 cm) min.] Straighten if needed
	Face ends to length	Face ends to length	Face ends to length
	Gundrill ID-small diameter	Gunbore ID-small diameter	Bore ID-small diameter
	Gunbore ID-large diameter	Gunbore ID-large diameter	--
	Gunbore ID radius (transition)	Gunbore ID radius (transition)	--
	Machine OD	Machine OD	Machine OD
	Restraighten if needed	Restraighten if needed	Restraighten if needed
	Grind OD	Grind OD	Grind OD
	Hone ID	Hone ID	--
	Cut OD spline	Cut OD spline	Cut OD spline
	Cut ID spline	Cut ID spline	Cut ID spline
	Heat treatment	Heat treatment	Heat treatment
	Shot peen	Shot peen	Shot peen
Starting material weight, lbs (kg)	173.7 (78.8)	90.0 (40.8)	90.0 (40.8)
Starting material cost per pound, (kg), $	0.32 (0.71)(1)	0.77 (1.71)(2)	0.32 (0.71)(1)
Scrap loss, lbs. (kg)	148.1 (67.2)	64.4 (29.2)	64.4 (29.2)
Value lost to scrap, $	$47.39	$49.50	$20.60

(1) Cost of AISI 4340 aircraft quality steel purchased--1973
(2) Quotation for 6000 foot quantity on August 26, 1974. Earliest delivery quoted for early 1976; actual cost would be at time of delivery. This cost would be expected to increase by at least 30 percent.

To facilitate the removal of the extrusion mandrel from the extruded tube, a small taper is required on the mandrel. This small taper on the extrusion mandrel will result in a very slight taper on the inside diameter of the extruded tube. Thus, it may be found important to increase the wall-thickness tolerance to ± 0.010 inch (± 0.025 μm).

To reduce the machining costs on the OD of the tubes, a change in surface finish is required from the 35 microinches (0.8 μm) called for to a 63-microinch surface finish. The 35-microinch surface finish can be achieved only by grinding, a more costly operation, whereas the 63-microinch surface finish can be achieved by conventional machining practices in a lathe, which is a more common shop machine. Since the OD of the tubes are to be shot peened anyway, the machining costs can be reduced by allowing lathe machining instead of grinding.

No other exceptions to surface finish, tolerances, and material specifications were anticipated.

Recommended Approach for Phase II

Battelle recommended that the warm HYDRAFILM extrusion process be used for producing tube blanks for later machining into torsion tube springs. The extruded tube blank dimensions are shown in Figure 2. It is expected that the inside surface of the tubes would require very little machining except for the preparation of the ID splines. The outside surfaces of the tubes would be finished to final shape by machining. This recommendation, based on the approach presented in the next few paragraphs, was approved, with minor modifications, by USATACOM.

Extrusion Tooling Concept

The tooling necessary for the warm HYDRAFILM extrusion of the torsion tube blanks is shown schematically in Figure 3. The tooling components needed for this program were designed to interface with the

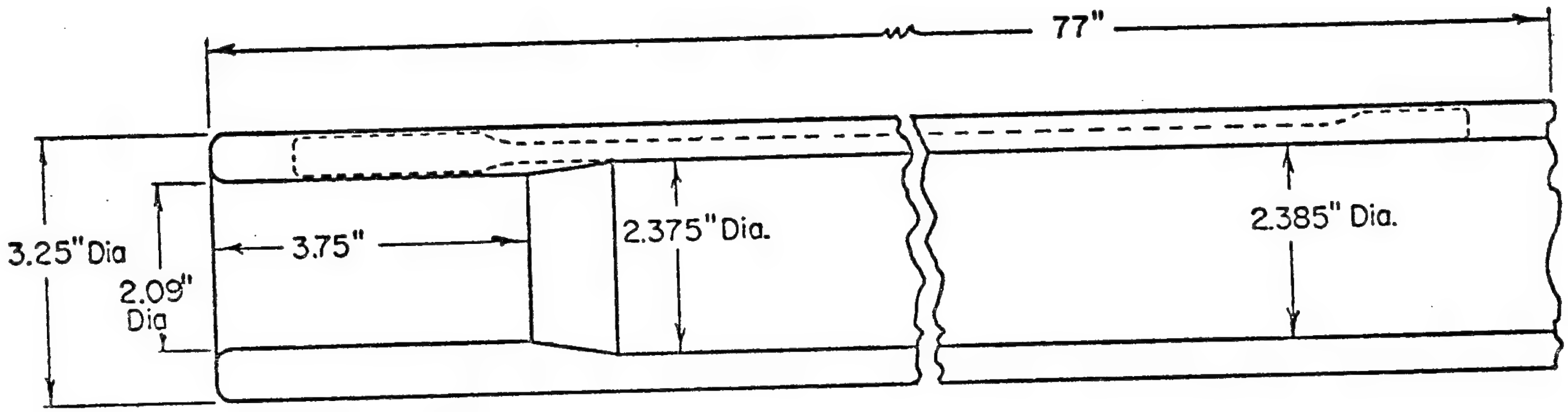


FIGURE 2. TORSION-TUBE BLANK TO BE PRODUCED BY HYDRAFILM EXTRUSION

The dashed drawing at the top represents where the torsion tube would be machined from the extrusion.

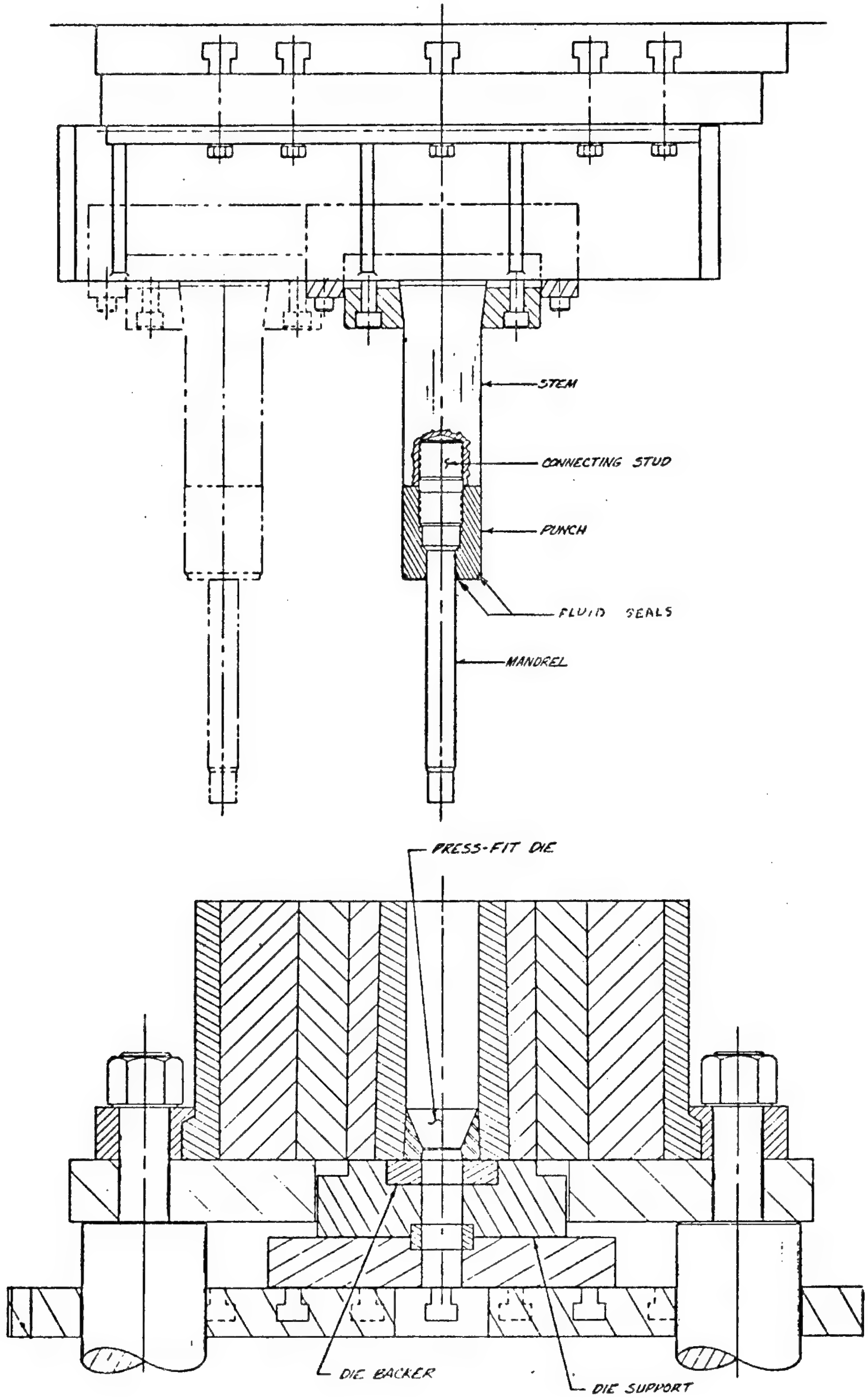


FIGURE 3. TOOLING SET-UP TO BE UTILIZED IN BATTELLE's 2500-TON PRESS FOR TORSION-TUBE EXTRUSION

basic tooling for Battelle's 2500-ton (25 MN) vertical hydraulic press. The tooling components designed and fabricated for this program include (1) the liner for the extrusion container, (2) dies, (3) mandrel, (4) punch and (5) seals for the mandrel and punch.

The liner was designed with a 6.25 inch (158.75-millimeter) diameter bore and was press-fit into Battelle's warm hydrostatic extrusion container. As shown in Figure 3, the 45-degree included angle die was press-fit into a tapered portion of the extrusion liner. Thus, the die is supported in the radial direction by the container. Loads in the vertical direction are supported by a die backer and other die support components.

The inside of the tube is formed against the mandrel as the billet material is extruded through the die. The mandrel was stepped to form the thicker wall for the internal splines, and was attached to the punch.

The punch applies the pressure to the lubricant-fluid and to the billet and dummy ring. The punch is attached to a stem, which in turn is attached to the upper platen of the press. The force from the ram of the press is transmitted to the billet through the stem and punch.

In the HYDRAFILM extrusion process, the hydrostatic fluid/ lubricant on both the inside and outside of the extrusion billet is pressurized to prevent or minimize contact of the billet with either the mandrel or wall of the extrusion container. Thus, high-pressure fluid seals are needed to seal the extrusion container. The tooling design illustrated uses two seals--a punch or ram seal for sealing against the extrusion container wall and a mandrel seal to preclude fluid leakage into the punch.

Extrusion Procedure

The tooling illustrated in Figure 3 was used to warm extrude a thick-walled tube blank [6.114-inch (155.3-millimeter) OD x 2.50 inch (63.5-millimeters) ID x 14 inches (355.6-millimeters) long]. For the Phase II experimental trials the billets were machined from 6.5-inch (16.5 cm)-diameter AISI 4340 aircraft quality steel bar. The billets

are coated with a water-base graphite lubricant, heated to the normal austenitizing temperature [1500 to 1550 F (815 to 843 C)] for AISI 4340 steel and then loaded into the extrusion container. A dummy ring is placed on the back end of the billet so that the 80-inch (203.2-centimeter) long extruded torsion-tube blank would drop freely from the die at the end of the extrusion stroke. During extrusion the ram and integral mandrel advance, first pressurizing the hydrostatic fluid, then contacting the dummy ring and billet. The ram and mandrel continue to advance at a pressing speed of about 40 inches per minute (16.9 millimeters per second) until enough of the dummy ring is extruded to assure that the torsion-tube blank is free of the die land.

After extrusion is completed, the ram and mandrel are retracted, freeing the extruded tube, which drops into a catcher-tube. The extrusion container is then raised and the die and extrusion discard (partially extruded dummy ring) removed from the die nest. The latter two items would be separated in a secondary operation. The extrusion cycle would be repeated using another die. It is anticipated that two or three dies would be circulating in the system in order to maintain a reasonable production rate.

Product Evaluation

After the torsion tube blanks are extruded, they are examined dimensionally and the ID surface finish determined. Should the as-extruded ID surface finish not be acceptable, the ID of the blanks will be honed.

Following dimensional inspection, the torsion-tube blanks are straightened, if necessary, to drawing tolerance. The small inside diameter and the exterior profile are machined on a lathe in preparation for machining of the internal and external splines. The machining of the splines, final heat treatment and shot peening of the exterior surfaces and splines per MIL-S-45387 was performed by Machine Products Company, Incorporated, LaCrosse, Wisconsin.

PHASE II - PROCESS DEVELOPMENT

The Phase II effort included (1) design of HYDRAFILM extrusion tooling, (2) HYDRAFILM extrusion of torsion-tube blanks, (3) machining of torsion tube springs from extruded blanks, (4) evaluation of the fabricated parts, and (5) estimation of fabrication costs for torsion-tube springs.

Design of Extrusion Tooling

The major part of the tooling design effort involved analysis of the liner for Battelle's extrusion container, the extrusion die, the mandrel and the fluid seals. The general configurations of these components and their locations in the tooling assembly were shown previously in Figure 3. Tool steel selection for these components was based on yield strength or hardness at use temperature. Resistance to abrasion at use temperature was not a primary consideration because of the limited number of trials to be accomplished.

Design of Extrusion Liner and Dies

The basic design problems were to calculate:

(1) Interfacial pressure (PI) needed to prestress the components and thus keep the stresses generated during extrusion at acceptable levels

(2) The interference between the component and its supporting structure to achieve the calculated prestress

(3) Load required to press-fit the component into place.

Thickwall-cylinder formulas are used to calculate the amount of prestress between components 1 and 2 that will keep the stresses on the bore of component 1 generated during extrusion to acceptable levels. Experience has demonstrated that zero is an acceptable value of

hoop stress (STRT) at the bore when a radial pressure equal to the desired pressure capability is applied. First, component 1 is treated as a free body and the pressure required on the die OD to give a zero value of hoop stress at the bore is calculated.

$$STRT = \{P1\ [(R1)^2 + (R2)^2] - 2(P2)\ (R2)^2\ (R1)^2\}/(R2)^2 - (R1)^2 \quad (1)$$

where

STRT = hoop stress at the ID of component 1 during extrusion. Ideally equal to zero

P1 = radial pressure on bore of component 1; the desired pressure capability

P2 = pressure on the OD of component 1; also, the pressure on the ID of component 2

R1 = internal radius of component 1

R2 = mean radius at interface between component 1 and 2.

Setting STRT = 0

$$P2 = (P1)\ (R1)^2\ [(R2)^2 + (R1)^2]/2(R1)^2\ (R2)^2 \quad (2)$$

Two components make up P2; a radial pressure, PR, caused by the internal pressure, P1, and the interference pressure, PI, generated by assembly of the two components. The value of PR is calculated and PI obtained by substraction.

$$PR = (P1)\ (R1)^2\ [(R3)^2 - (R2)^2]/(R2)^2\ [(R3)^2 - (R1)^2] \quad (3)$$

where R3 = outer radius of component 2. The use of this equation assumes that both components are acting as a single elastic body. Then,

$$PI = /P2/ - /PR/ \quad (4)$$

In the case where a liner is being designed, the interfacial pressure PI prestresses the liner (component 1) and expands the support container (component 2). When these equations are used for design of press-fit dies, component 1 is the die and the extrusion container, including the liner, becomes component 2.

The radial deflection at the interface (interference) required to generate the interface pressure is determined by calculating the

strains generated at the ID of component 2 and the OD of component 1 by the application of PI to them and adding their absolute values.

$$\text{DELR} = /\text{DELR1}/ + /\text{DELR2}/ \tag{5}$$

$$\text{DELR1} = [(\text{PI})\ (\text{R2})/\text{E1}]\ \left\langle \{[(\text{R1})^2 + (\text{R2})^2]/[(\text{R2})^2 - (\text{R1})^2]\} - \text{NU1} \right\rangle \tag{6}$$

$$\text{DELR2} = [(\text{PI})\ (\text{R2})/\text{E2}]\ \left\langle \{[(\text{R3})^2 + (\text{R2})^2]/[(\text{R3})^2 - (\text{R1})^2]\} + \text{NU2} \right\rangle \tag{7}$$

where

DELR = required radial interference between components 1 and 2

DELR1 = radial contraction of OD of component 1

DELR2 = radial expansion of ID of component 2

E1 = elastic modulus of component 1

E2 = elastic modulus of component 2

NU1 = Poissons ratio of component 1

NU2 = Poissons ratio of component 2.

Next, the load, L, needed to press-fit component 1 into the tapered portion of component 2 is calculated. This must overcome the vertical components of the force needed to prestress component 1 and the frictional losses due to sliding between components 1 and 2.

$$L = (\text{PI})\ S\ [\sin\theta + (\text{MU})\cos\theta] \tag{8}$$

where

S = exterior surface area of component 1

MU = assumed coefficient of friction between components

θ = angle of taper on OD of component 1 (it is practice to have a matching taper on ID of component 2).

If the load calculated is greater than the hold down available on the extrusion press, the angle θ is reduced, if possible, or PI is reduced. When it is necessary to reduce the magnitude of PI because of lack of load capability, obviously the hoop stress at the ID of component 1 will not be zero during extrusion and should be calculated.

The dimensional and stress conditions used for design of the extrusion liner and dies in this program are given in Table 2. The configuration of the components are shown in Figure 4.

Design of Stem, Punch and Mandrel

A detailed view of the punch assembly is shown in Figure 5. Alignment of the mandrel with the punch is accomplished by specifying a 0.001-inch (0.025-millimeter) tolerance band for the mandrel OD and the ID of the punch (see Figures 6 and 7). In addition, seating of the 45 degree chamfer on a mating chamfer in the punch increases the probability that the two parts will be concentric when assembled.

The dimensions of the double-ended stud (see Figure 8) were selected to insure seating of the mandrel to the previously mentioned chamfer in the punch. The enlarged diameter on the stud acts as an alignment ring during assembly of the punch and mandrel to the stem.

The materials used and the hardnesses to which each component was heat treated and indicated on the Figures.

Design of Stem and Mandrel Seals

To obtain the advantages of the HYDRAFILM extrusion process, it is necessary to pressurize the fluid/lubricant on both the inside and outside of the billet. These pressures are expected to be on the order of 160,000 psi (1103.2 MPa). In addition, the fluid/lubricant will be heated by the billet to temperatures approaching 1550 F (843 C). Thus, the seals must operate at high pressures and high temperatures.

The important early work in developing high pressure seals was done by Bridgeman[3]. He developed and used a sealing method based on the concept of an unsupported area. The design involves a sealing interface at which the pressure is greater than the fluid pressure in the chamber. This condition is achieved by supporting the metal seal on an annular ledge of a stem that has a plan area smaller than that annular

TABLE 2. DESIGN DATA FOR HYDROSTATIC EXTRUSION LINER AND EXTRUSION DIES

Component	Taper Angle, θ	Mean Radii, in.			Design Pressure psi, P1	Calculated Parameters		
		R1	R2	R3		PI, psi	DELR, in.	L, tons
Extrusion liner	1.0	3.125	5.25	18.0	230,000	78,000	0.049	2750
Extrusion die	2.5	1.625	3.283	18.0	200,000	76,740	0.023	300

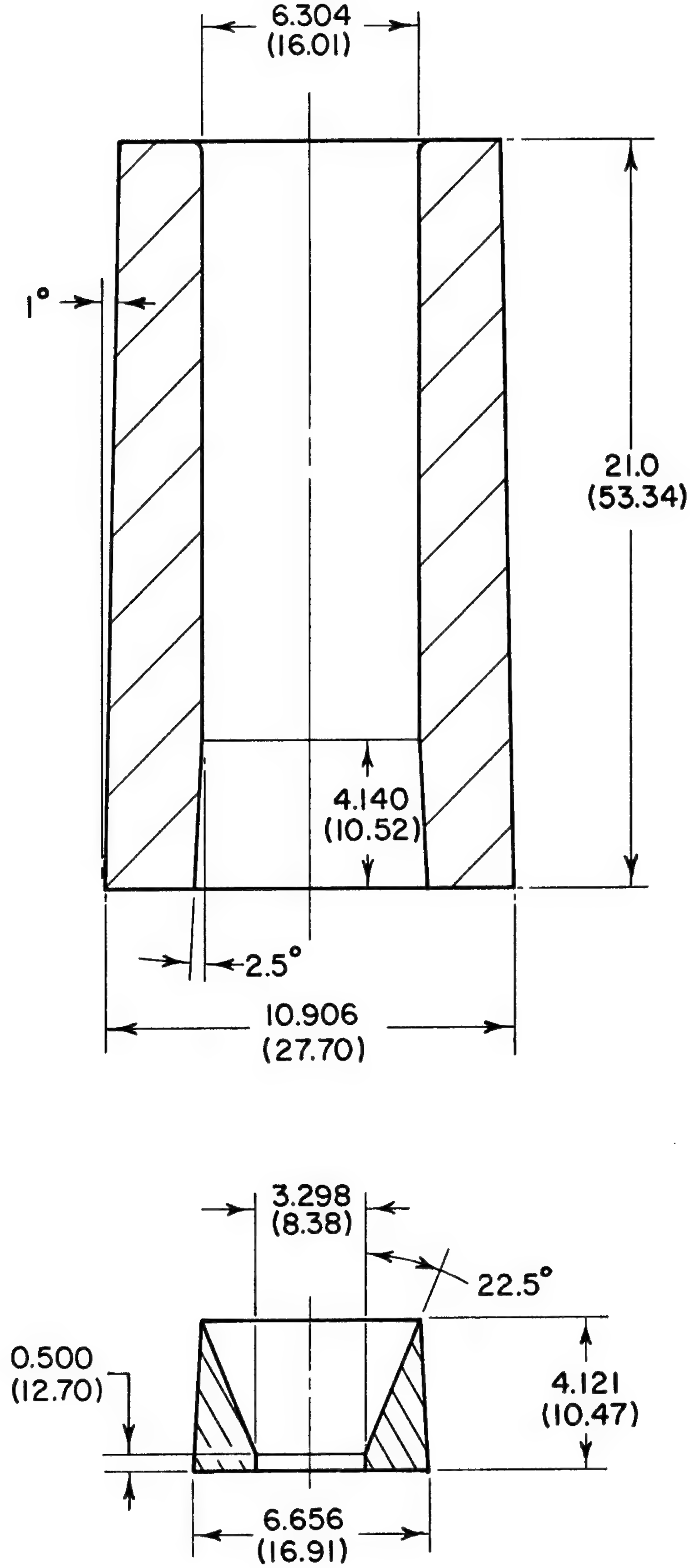


FIGURE 4. MANUFACTURED DIMENSIONS OF EXTRUSION LINER AND DIES

Both were fabricated from H-11 tool steel and heat treated to obtain a hardness of R_c 53/55. All dimensions in inches (centimeters).

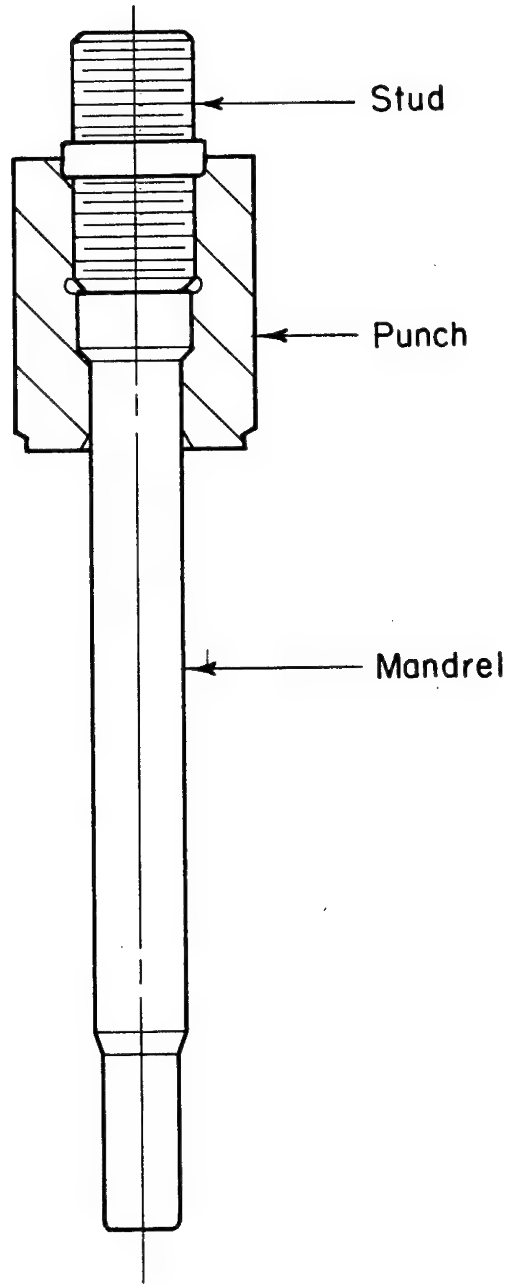


FIGURE 5. ASSEMBLY DRAWING OF PUNCH AND MANDREL

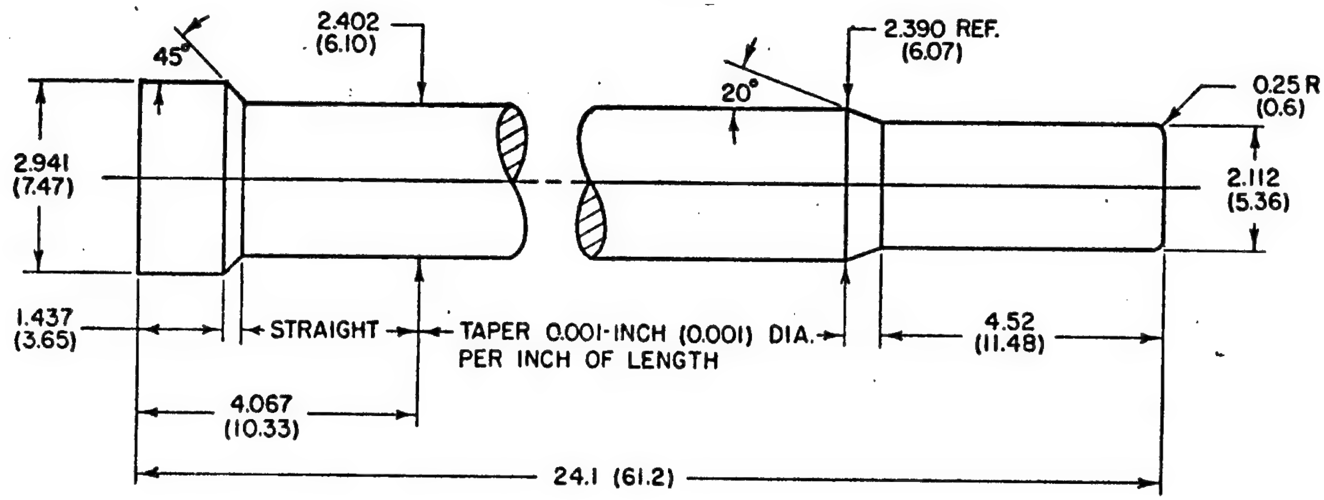


FIGURE 6. EXTRUSION MANDREL
Material: H-11 Tool Steel
Hardness: R_c 52/54

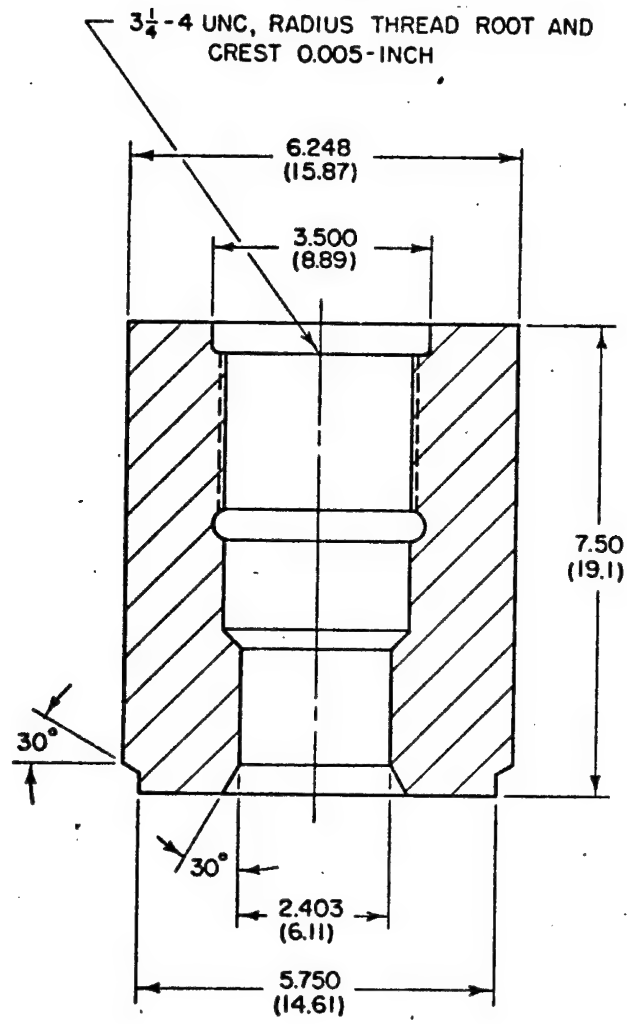
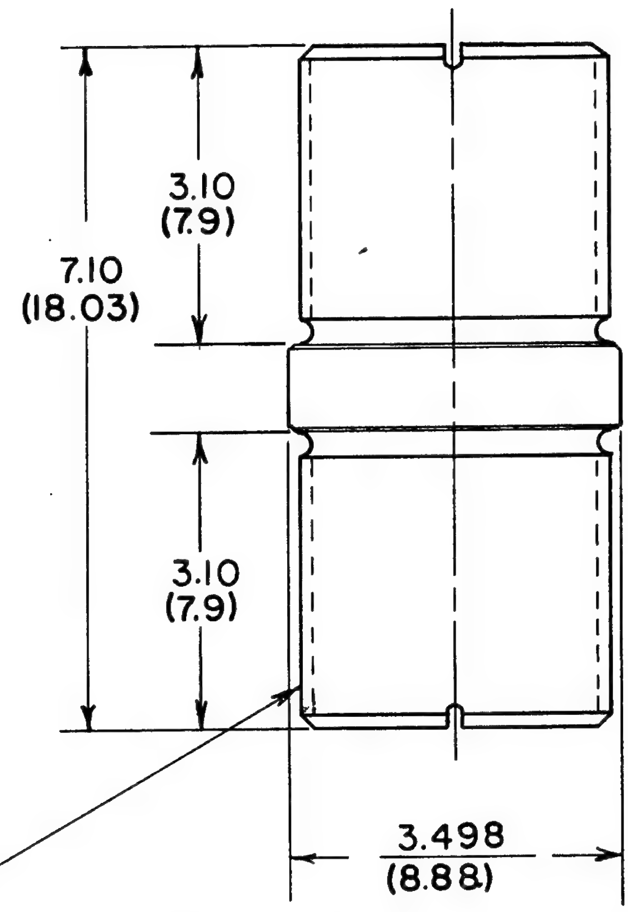


FIGURE 7. EXTRUSION PUNCH

Material: H-11 Tool Steel
Hardness: R_c 52/54



$3\frac{1}{4}$- 4 UNC, RADIUS THREAD ROOT AND CREST 0.005- INCH BOTH ENDS.

FIGURE 8. ATTACHMENT STUD

Material: 4340 steel

Hardness: R_c 36/38

area over which the fluid pressure is applied. Most of the seal designs developed since the original work by Bridgman have been based, at least in part, upon the concept of an unsupported area.

A seal system often used for hydrostatic extrusion consists of an O-ring made from one of many available elastomeric materials and a metal miter ring. The O-ring provides sealing at low fluid pressures where the miter ring is not yet effective. In addition to providing the high pressure seal, the metal miter ring prevents extrusion of the O-ring into the clearance between the punch and extrusion container.

The selection of elastomeric material from which the O-ring is fabricated is based on use temperature and chemical properties of the fluid. Buna-N rubber is commonly used for hydrostatic extrusion.

The major parameters considered in the design of metal miter ring seals include (1) the angle (see Figure 9), (2) surface area in contact with the container, (3) friction properties of the material, and (4) strength properties of the material. The face width, w, of the miter ring is usually dictated by the size availability of O-rings with an outer diameter equal to the bore diameter of the extrusion container.

An analysis[4] of the forces acting on the miter ring revealed that the geometric dimensions (angle θ and ring height, h) and friction conditions have a considerable influence on the pressure at which the seal begins to work. A graphical summary of these results is presented in Figure 10. For a fixed value of material yield strength, increasing the ring height and/or friction coefficient increases the fluid pressure at which the miter ring becomes effective, i.e., the pressure at which sealing will occur. Since we have necessarily fixed w, the face width, of the miter ring, increasing the height implicitly decreases the angle θ.

For the miter ring to seal at low fluid pressures, one would select a low yield strength material for the seal. However, one must also determine whether the miter ring will extrude into the clearance between the ram and the container. The potential for this occurring

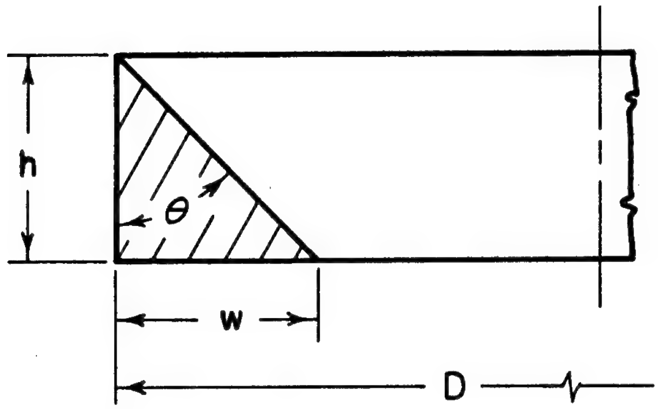


FIGURE 9. CROSS-SECTION OF METAL MITER RING SEAL

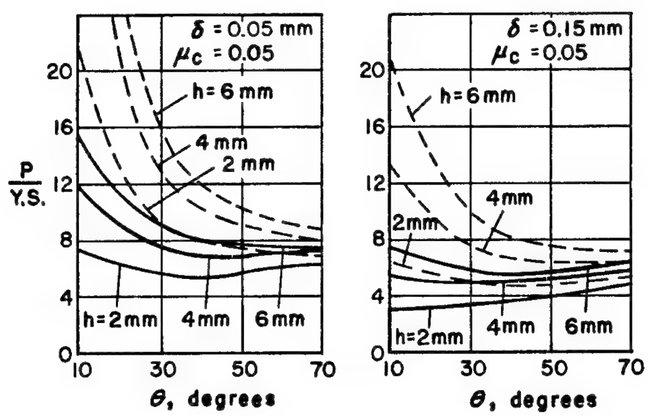


FIGURE 10. PRESSURE DEPENDENCE OF THE WORKING FLUID AT WHICH TIME THE SEAL OPERATES ON THE SHAPE AND CROSS-SECTIONAL DIMENSIONS AND CONTACT SURFACE FRICTION CONDITIONS (h = ring height, μ_s = friction coefficient between stem and seal; μ_c = friction coefficient between container and seal; and μ_s = 0.015; μ_s = 0.005; δ = radial clearance between punch and container.[4]

can be estimated. For a clearance of known dimensions and a miter ring of known flow stress, the approach consists of estimating:

(1) The extrusion ratio corresponding to forcing the miter ring into the radial gap

(2) The pressure required to extrude the miter ring material to the reduction described in (1) with a die having an appropriate included angle.

If the estimated extrusion pressure is higher than the anticipated maximum fluid pressure, the probability of the miter ring extruding enough to cause trouble is low. Figure 11 is a chart that has been used at BCL for estimating the material yield strengths needed to prevent extrusion of the miter ring when pressurizing extrusion containers to various pressure levels. For most cases, the "extrusion ratio" is on the order of 10 to 12:1. Referring to Figure 11, one projects material yield strength requirements in the 25 to 50 ksi (172.4 to 344.7 MPa) range.

The remaining parameter to be selected is the angle, θ, which in turn defines the height, h, of the miter ring. Referring to Figure 10, one observes that angles in the range of 40 to 60 degrees and small miter ring heights are preferred from the standpoint of minimizing the pressure level at which the seal deforms plastically.

With large diameter miter rings, the friction losses due to sliding of the stem seal against the extrusion container may be quite large. The approximate magnitude of this loss is given by

$$F_{fc} = P \operatorname{ctn} \theta \quad \mu_c \pi D h \tag{9}$$

But, since w, the seal width, is fixed because of size availability of commercial O-rings, h is also a function of θ

$$h = w \operatorname{ctn} \theta \tag{10}$$

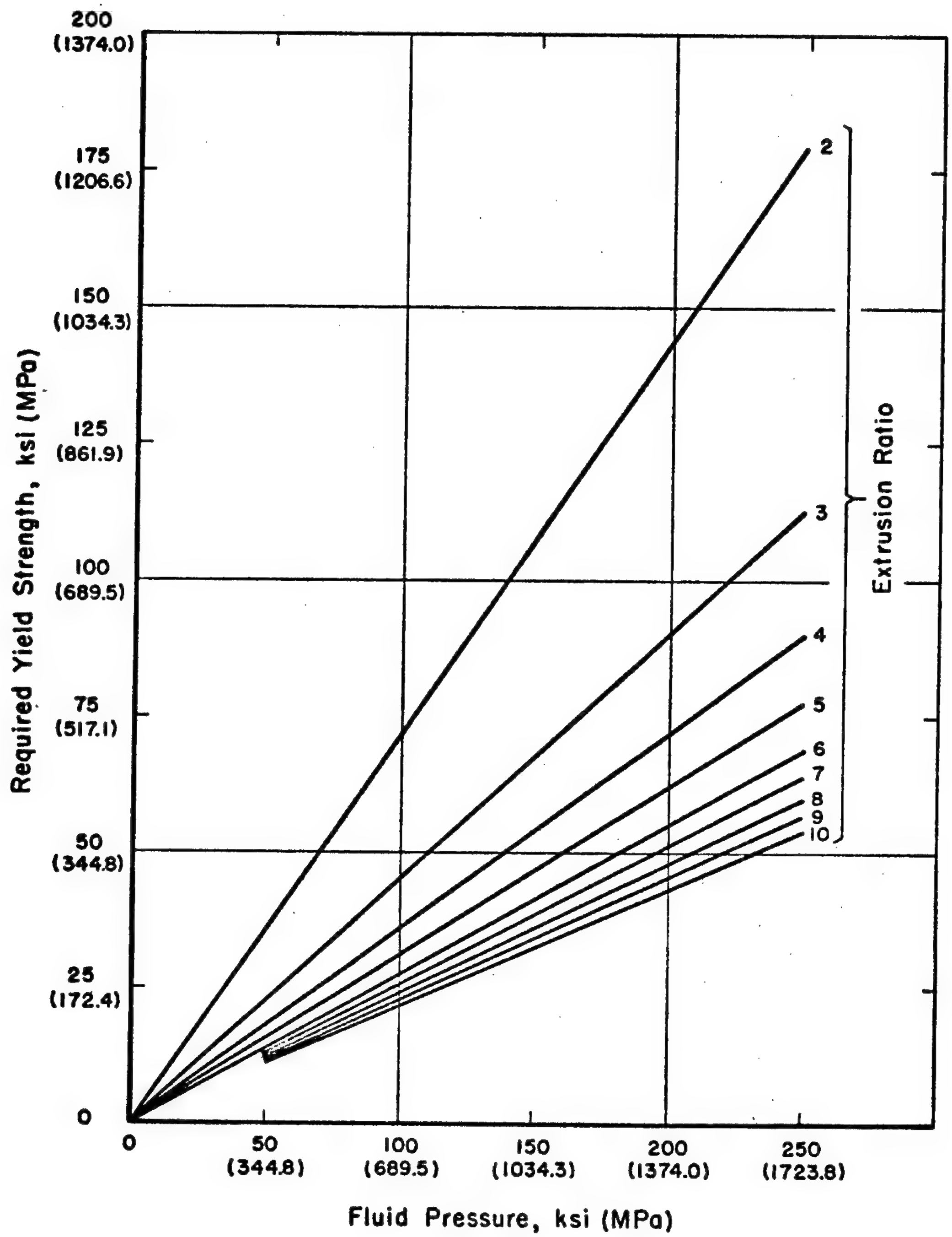


FIGURE 11. CHART FOR ESTIMATING MATERIAL YIELD STRENGTHS REQUIRED TO PREVENT EXTRUSION OF THE MITER RING SEAL

The dimensions of the stem and mandrel miter ring seals used for this program are indicated in Figure 12. An angle of 60 degrees was selected for the stem seal in order to minimize friction losses. Since the mandrel seal is "fixed" in place and is to be used without an O-ring, the angle was selected to obtain sealing at lower fluid pressures.

Extrusion of Torsion Tubes

The objectives of the HYDRAFILM extrusion trials were:

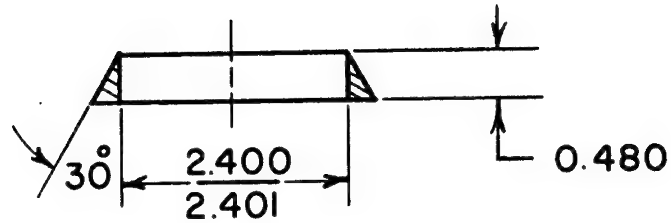
(1) Determine parameters necessary for extrusion of up to 20 torsion tube blanks
(2) Determine the feasibility of using thermo-mechanical processing procedures for fabricating torsion blanks
(3) Test the validity of production rate assumptions made for the cost analysis
(4) Verify the tooling design concept.

The process parameters to be investigated included (1) preform design, (2) hydrostatic fluid/lubricant and, (3) cooling rate from extrusion temperature.

Experimental Procedures

Preform Fabrication and Preparation. The small number of trials projected for this program could not economically justify the use of warm forming methods for fabrication of the preforms. Therefore, conventional machining techniques were used to make the preforms (see Figure 13) from 6-1/2-inch (165.1 millimeter)-diameter aircraft quality 4340 steel bar. The machining sequence used was:

(1) Saw to length -- 14-1/4 ± 1/8-inch (361.9 ± 3.2 millimeter)
(2) Face to length -- 14.00-inch (35.6 cm)
(3) Gun drill
(4) Machine OD
(5) Bore 2.09-inch (5.3 cm) diameter.



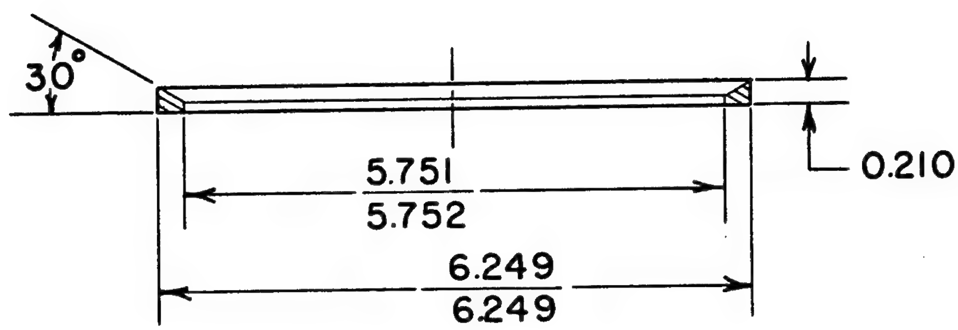


FIGURE 12. DIMENSIONS OF STEM AND MANDREL MITER RING SEALS

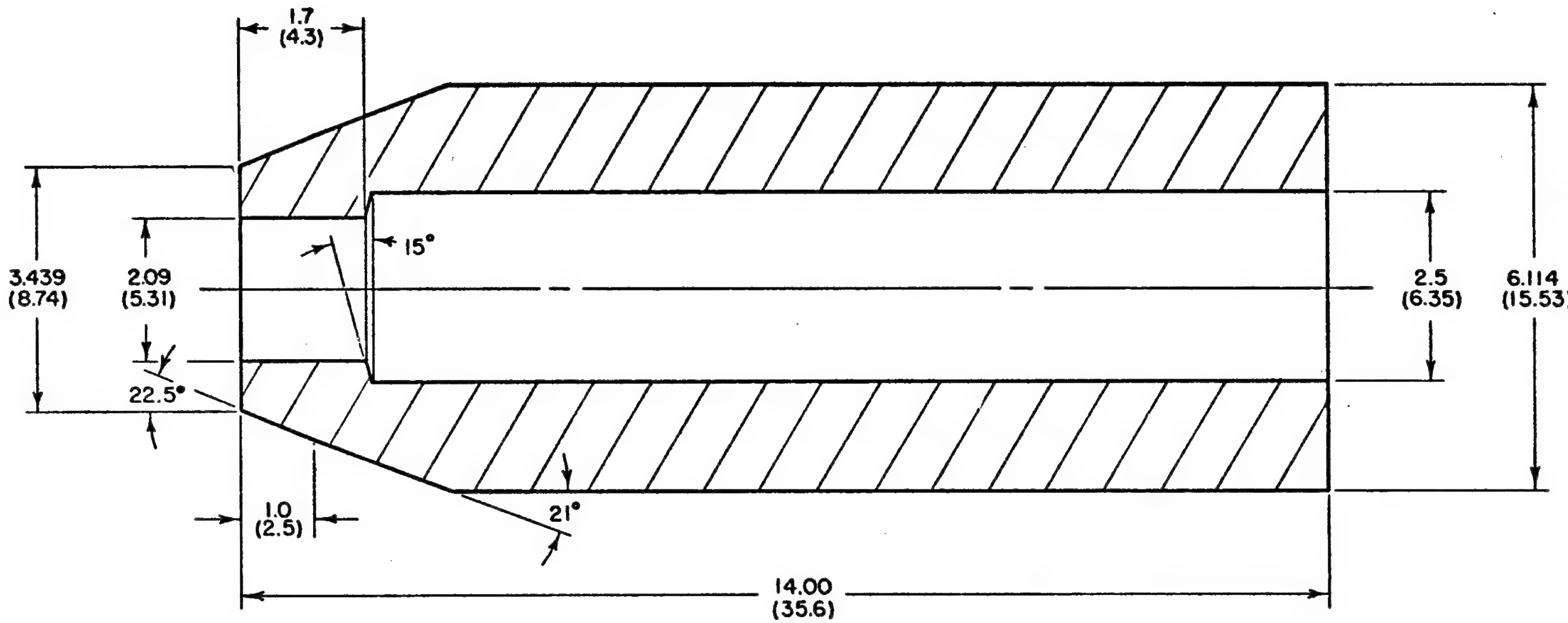


FIGURE 13. EXTRUSION PREFORM, ORIGINAL DESIGN

To facilitate loading of the hot preform and pusher block into the extrusion container, these two components plus a graphite washer were assembled by tack welding to provide a single assembly. This is shown in Figure 14.

These assemblies were then heated to about 300 F (149 C) and spray coated with Acheson Colloids Deltaforge 144* diluted 5:1 with water. The resulting coating was about 0.01-inch (0.02 cm) thick. A group of these are shown in Figure 15.

Sequence of Operations. The sequence of events described applies to all experimental trials conducted. Minor variations will be discussed later. A typical operational sequence included:

(1) Load coated billet assembly into furnace
(2) Preparation of tooling
    (a) Press-fit extrusion die into container
    (b) Preheat die and mandrel to 500 F (260 C) with gas burner
    (c) Apply lubricant to die and mandrel
(3) Transfer heated billet assembly to container and load (see Figure 16)
(4) Lower mandrel to "seal-position" (see Figure 17)
(5) Inject hydrostatic fluid (see Figure 18)
(6) Initiate extrusion cycle
(7) Post extrusion operations
    (a) Removal of extrusion butt and die
    (b) Removal of extrusion from catching device.

Extrusion Trial Results

First Series of Trials. The objectives of the first series of experimental trials were to (1) ascertain if any tooling design changes would be necessary, (2) determine the procedures required to achieve

*A water-base graphite lubricant manufactured and sold by Acheson Colloids Company, Port Huron, Michigan.

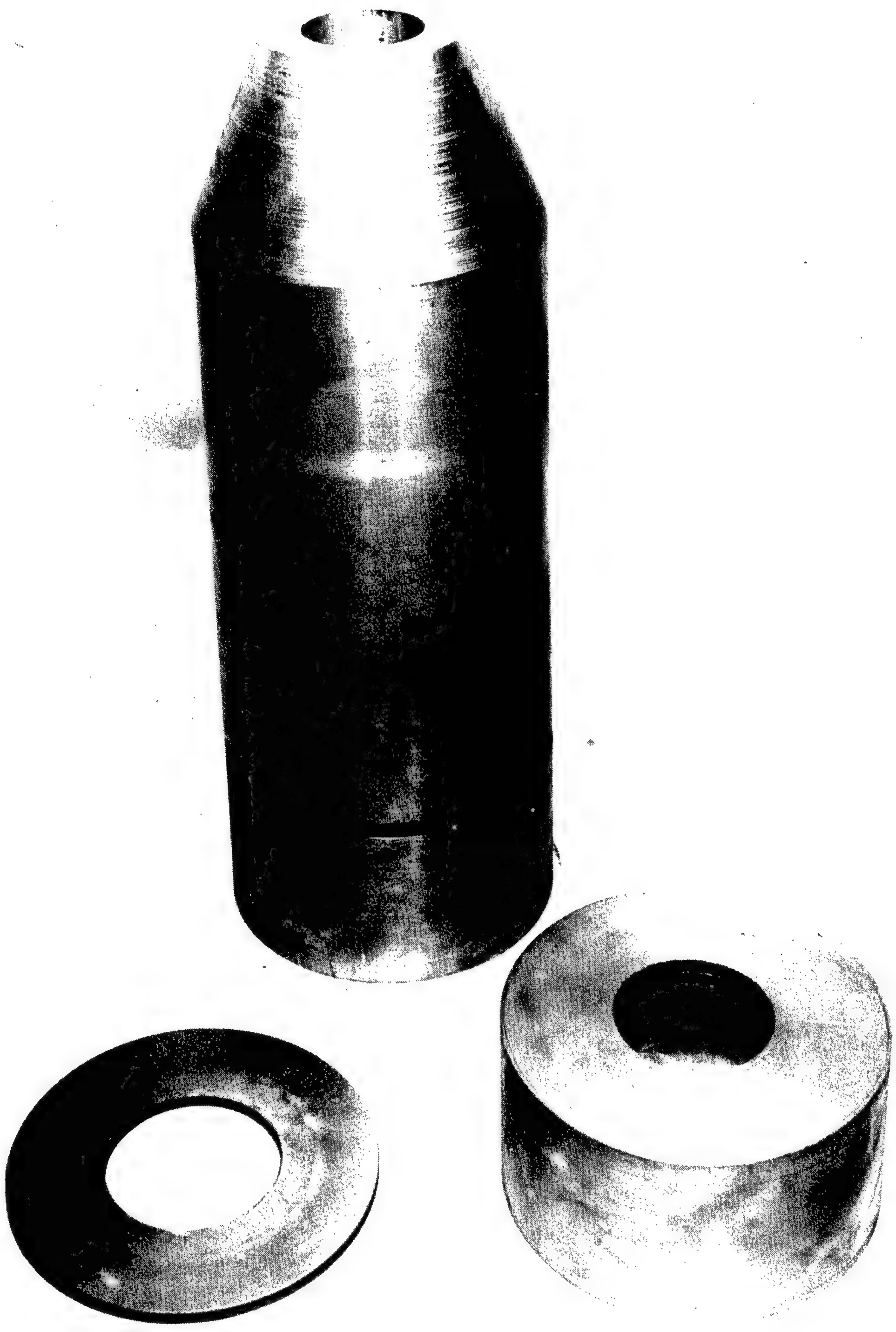


FIGURE 14. EXTRUSION PREFORM-PUSHER BLOCK ASSEMBLY

FIGURE 15. COATED HYDRAFILM EXTRUSION BILLETS

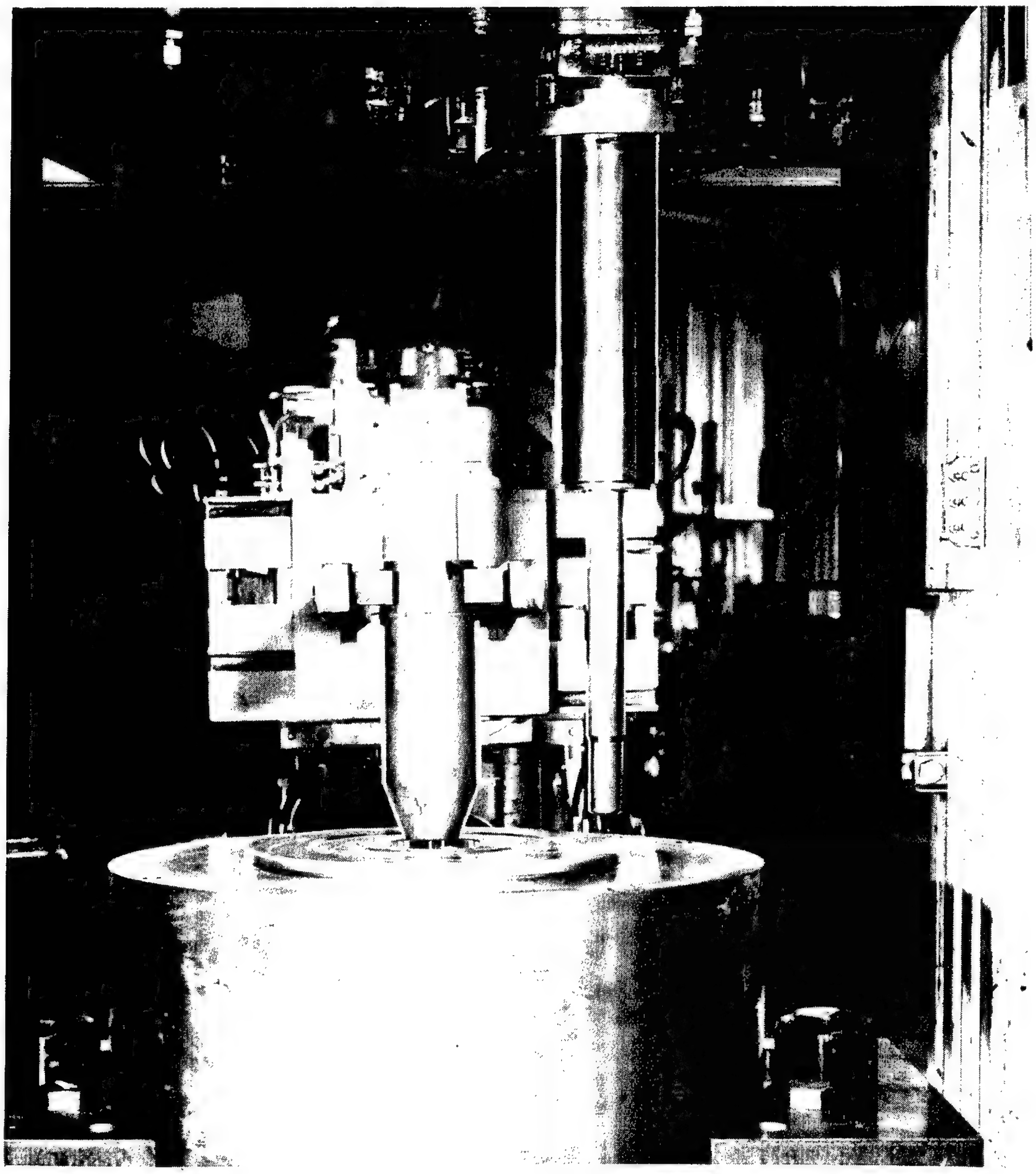


FIGURE 16. LOADING OF EXTRUSION BILLET ASSEMBLY INTO HYDRAFILM EXTRUSION CONTAINER

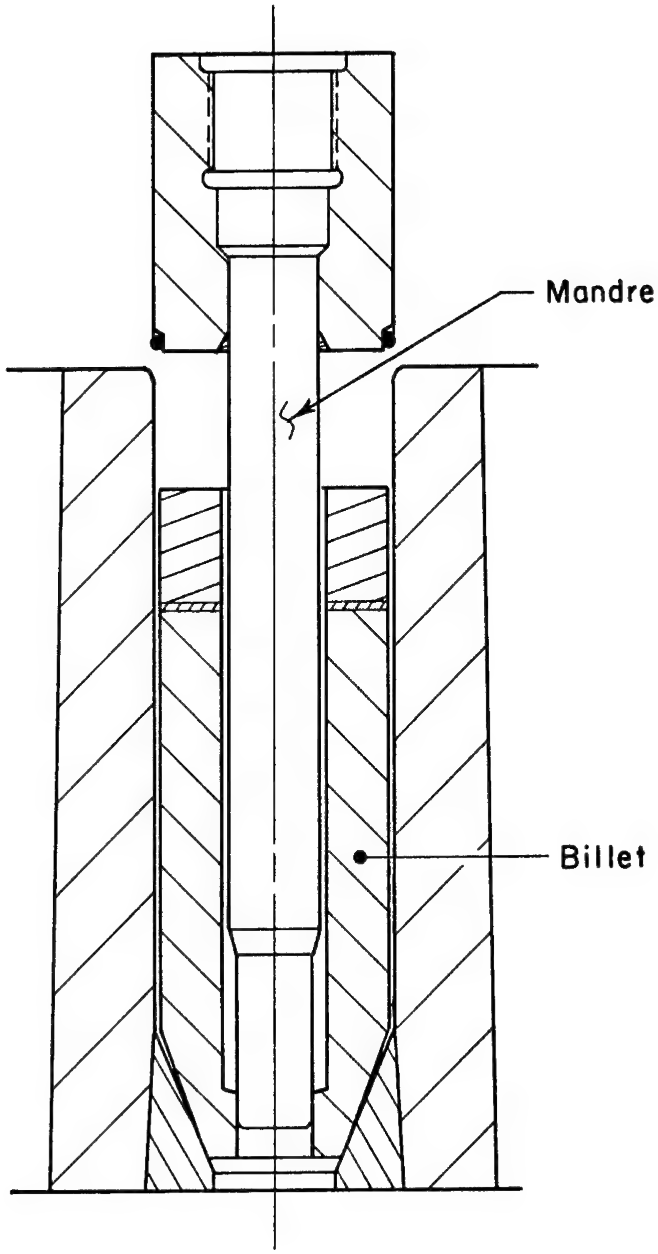


FIGURE 17. EXTRUSION MANDREL LOWERED TO "SEAL-POSITION"

FIGURE 18. INJECTION OF HYDROSTATIC FLUID INTO HYDRAFILM EXTRUSION CONTAINER

separation of the extruded product from the extrusion butt, and (3) develop the preform shape needed to fabricate the torsion tube blanks.

The data from these six trials are given in Table 3. Trial No. 1 had to be stopped before obtaining a complete extrusion because of a stem seal leak. For Trial No. 2 and all subsequent trials, the height h, of the stem-seal miter-ring was decreased 0.037-inch (0.09 cm). This solved the stem seal problem. After completion of Trial No. 3, it was observed that fluid was seeping from the joint between the punch and stem. Disassembly revealed that hydrostatic fluid and lubricant had been forced past the mandrel seal and around the connecting stud (see Figure 5). Replacement with a new seal did not solve the problem. Thus, the material for this miter ring seal was changed from 4340 hardened to Rockwell C 34 to 36 to annealed copper for Trial No. 5. No mandrel seal leaks were observed.

Separation of the extruded product from the extrusion butt was not achieved when castor oil was used for the hydrostatic fluid. Piping of the last portion of the billet as it passed through the die formed a gap through which the pressurized castor oil-lubricant mixture was expelled from the container. This stopped the extrusion operation and left a small portion of unextruded billet in the die.

Changing to a more viscous fluid (Acheson Colloids 1773 C extrusion lubricant) allowed retention of sufficient fluid to continue the extrusion operation and eject all of the product from the die land. Typical extrusion curves for these two conditions--complete and partial separation--are shown in Figure 19.

Initial evaluation of configuration and dimensions of extrusion Nos. 1, 2 and 3 revealed (1) the presence of a "notch" on the ID near the nose (see Figure 20), (2) the heavy wall section of the extrusion was about 6 to 7 inches (15.2 to 17.8-centimeters) too long, (3) the total length of the extruded products was about 4 to 6 inches (11.2 to 15.2 centimeters) short, and (4) the parts were bowed--straightness of about 3/4-inch per foot (0.63 millimeter per centimeter).

TABLE 3. RESULTS OF WARM HYDROSTATIC EXTRUSION TRIALS FOR PRODUCING TORSION TUBE BLANKS FROM AIRCRAFT QUALITY 4340 STEEL

Trial Number	Billet Temperature, F	Reduction Ratio	Extrusion Pressure, ksi		Fluid Type	Comments
			Breakthrough	Runout		
1	1700	6.4	--	84.1	A	Stem seal leak; obtained 2 ft. of tube.
2	1550	6.4	115.7	109.9	A	Complete extrusion; separation not achieved.
3	1550	6.4	109.9	106.3	A	Mandrel seal leak; complete extrusion; separation not achieved.
4	1550	6.4	110.4	106.1	B	Mandrel seal leak; complete extrusion; separation achieved.
5	1550	6.4	108.0	105.2	B	Complete extrusion; no seal leaks.
6	1550	6.4	113.8	109.0	B	Complete extrusion; separation achieved; no seal leaks.

(A) Castor oil
(B) Acheson Colloids 1773 C.

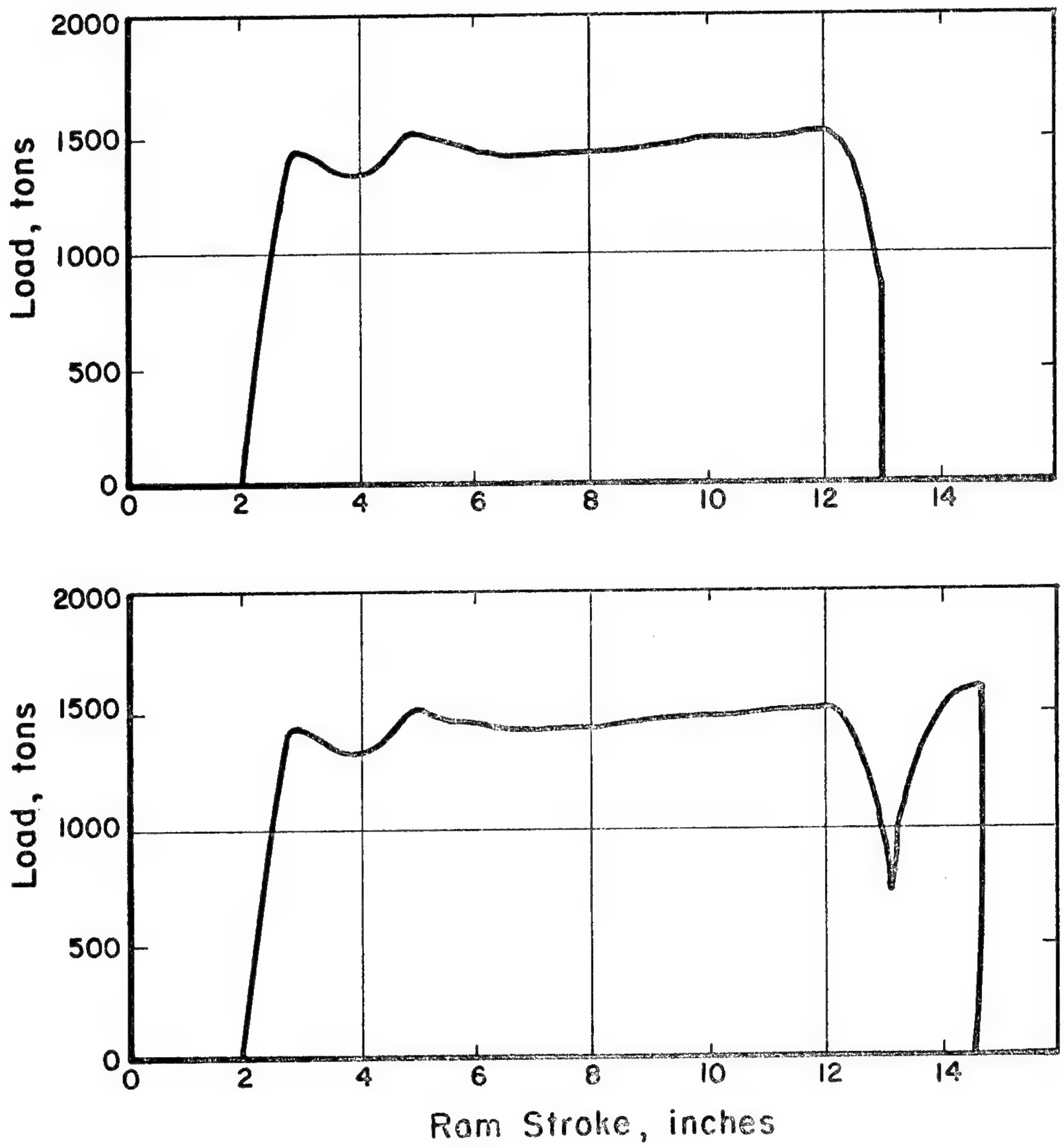
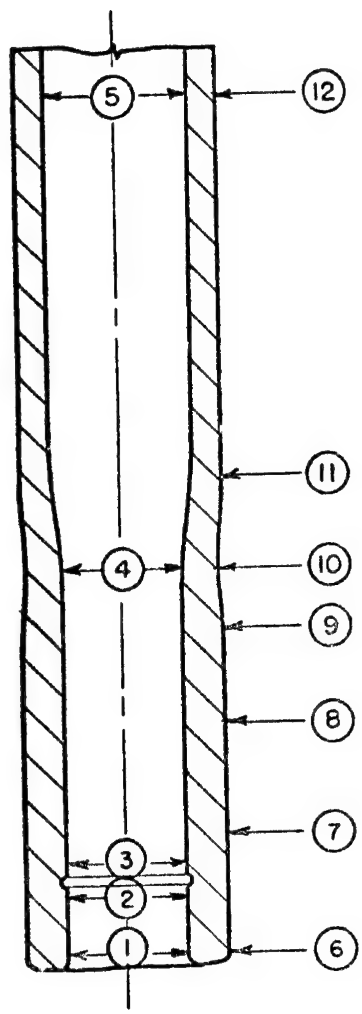


FIGURE 19. TYPICAL WARM HYDRAFILM EXTRUSION CURVES

Upper curve: separation not achieved
Lower curve: separation achieved



Extrusion Number	Measurement Station	Distance from Nose, inch	Dimensional Measurement, inch
1	1	0	2.134
	2	2.7	2.099
	3	2.7+	2.099
	5	24	2.369
	7	4	3.253
	8	8	3.247
	9	12	3.249
	10	14	3.190
	11	17	3.243
	12	24	3.243
2	1	0	2.122
	2	2.7	2.100
	3	2.7	2.100
	4	11	2.098
	6	0	3.270
	7	4	3.250
	8	8	3.244
	9	11	3.190
	10	14	3.269
3	1	0	2.120
	2	2.7	2.101
	3	2.7	2.101
	6	0	3.265
	7	4	3.244
	8	8	3.240
	9	10-1/2	3.186
	10	12	3.241
	11	14	3.239

FIGURE 20. INTERNAL CONFIGURATION AND DIMENSIONS OF NOSE SECTIONS OF EXTRUSION NUMBERS 1, 2 and 3

The presence of the notch on the ID was believed to be caused by the sharp transition angle (75 degrees) between the two ID's of the billet. For Trial No. 4, this angle was changed to 45 degrees. This change did not eliminate the notch but did decrease its severity. Modifying the chamfer to a 30-degree angle (Trial No. 5) resulted in elimination of the ID notch in the extruded product.

The length of thick-walled section formed during extrusion is primarily a function of the relative position of the mandrel with the preform and the die. If the distance is too great (see Figure 21a), the thick-wall section will be too long.

For Trial No. 6, the billet was modified by (1) moving the 30-degree ID chamfer toward the nose [about 0.35-inch (0.9 cm)] and (2) decreasing the thickness of the pusher block by about 0.8-inch (2.0 cm). The relative position of the mandrel with this modified billet and the die is shown in Figure 21b. These modifications were successful in reducing the length of the thick-wall section of the extrusion to about 4-1/4 inches (10.8 centimeters).

After completion of six extrusion trials it had been determined that (1) separation of the extruded product from the extrusion butt could be achieved as part of the extrusion sequence, (2) minor modifications to the extrusion billet geometry were needed to obtain the correct length of the thick-wall section of the tubes, (3) length of the extruded product was short and (4) straightness of the as-extruded tubes would not meet the requirements for the finished component without a separate straightening operation.

Second Series of Trials. Having determined the changes necessary to obtain the desired product dimensions, the objectives of the second series of extrusion trials were (1) to fabricate 20 torsion tube blanks which could be machined to the torsion tube spring configuration and (2) use thermomechanical processing (TMP) techniques to fabricate up to 5 torsion tube blanks. The first series of trials had demonstrated the feasibility of separating the extruded product from the extrusion butt--the only remaining procedure to finalize was oil quenching from extrusion temperature for the TMP tubes.

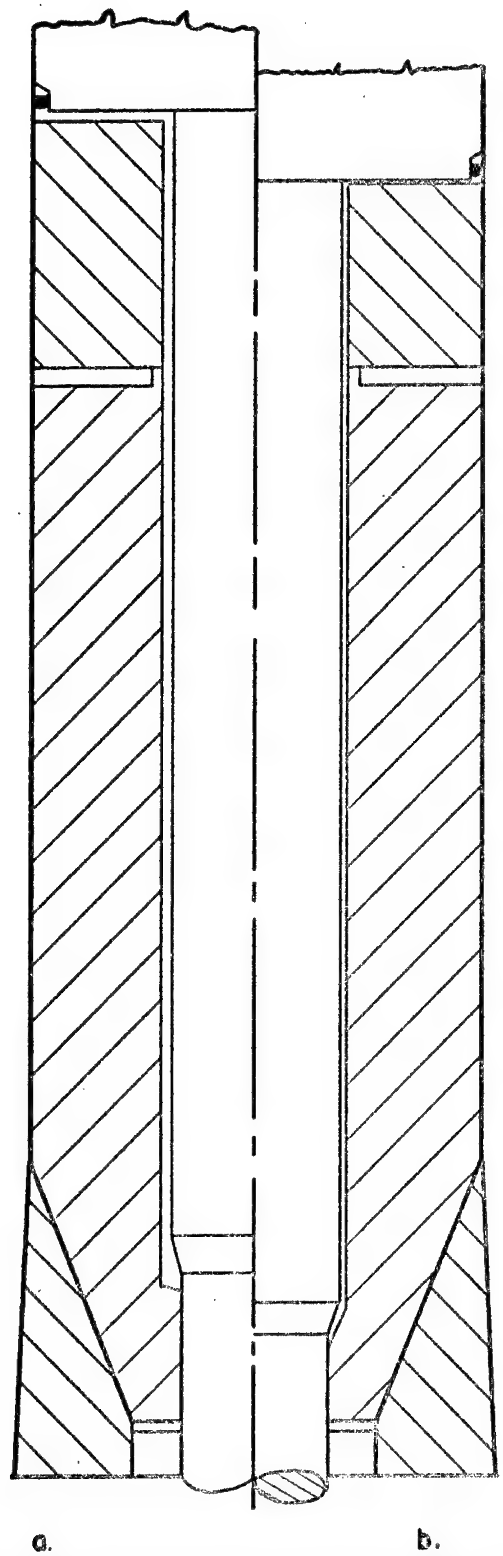


FIGURE 21. RELATIVE POSITION OF MANDREL WITH PREFORM AND DIE.
(a) LEFT SIDE IS ORIGINAL PREFORM DESIGN
(b) RIGHT SIDE IS MODIFIED PREFORM DESIGN

Increasing the reduction ratio to 7.5:1 by decreasing the OD of the extrusion to 3-1/8 inch (7.9 cm) provided extruded blanks that were long enough to fabricate the torsion tube springs. The increase in extrusion pressure for this greater reduction was nominal--about 10,000 psi (69 MPa). The data for this second series of trials are given in Table 4.

Attainment of the program objectives were in sight when, as indicated in Table 4, mandrel seal leaks were again encountered during the conduct of Trial No. 10. It had appeared that the seal design modifications made during the course of the first series of trials had solved the problem (no mandrel seal leaks were observed during Trials 5 through 9). Extensive attempts to separate the mandrel and punch assembly from the stem so the seal could be repleaced were not successful. Attempts to repair the mandrel seal in place were not successful as evidenced by the occurrence of seal leaks in Trials Nos. 11 and 12. As the extrusion cycle for Trial No. 13 was being completed, the extrusion stem failed. Up to this time, the tubes being produced were long enough to make torsion tube springs, but were still bowed.

The fracture consisted of three approximately 9-inch (23-centimeter) long radial cracks originating at the 3-1/4-inch (8.3 cm) ID of the threaded portion of the stem and propagating completely through the wall thickness and into the solid portion of the H-11 tool steel. The magnitude of the hoop stress [approximately 195 ksi (1344.5 MPa)] generated in the cylindrical portion of the stem by pressurized [109 ksi (751.6 MPa)] fluid being forced into the chamber plus the stresses generated in the stem by the load needed to extrude the tube was sufficient to initiate and propagate a crack through the 1.45-inch (3.7 cm) thick section of the stem.

TABLE 4. RESULTS OF WARM HYDROSTATIC EXTRUSION TRIALS FOR PRODUCING TORSION TUBE BLANKS FROM AIRCRAFT QUALITY 4340 STEEL

Trial Number	Billet Temperature, F	Reduction Ratio	Extrusion Pressure, ksi (MPa) Breakthrough		Runout		Fluid Type	Comments
7	1550	7.5	152.0	(1048.0)	124.3	(8570)	B	Complete extrusion; separation not achieved.
8	1550	7.5	130.0	(896.4)	116.6	(804.0)	C	Complete extrusion.
9	1550	7.5	128.1	(883.3)	119.5	(824.0)	C	Complete extrusion; separation achieved.
10	1550	7.5	130.0	(896.4)	120.4	(830.2)	C	Complete extrusion; separation achieved; mandrel seal leak.
11	1550	7.5	125.2	(863.3)	115.7	(797.8)	C	Complete extrusion; separation achieved; mandrel seal leak.
12	1550	7.5	120.4	(830.2)	113.8	(784.7)	C	Complete extrusion; separation achieved; mandrel seal leak.
13	1550	7.5	120.4	(830.2)	109.0	(751.6)	C	Complete extrusion; separation achieved; mandrel seal leak, fractured extrusion stem.

(B) - Acheson Colloids 1773 C.
(C) - Fiske-BMI No. 4.

Dimensional Evaluation of Extrusions

The dimensional evaluation included (1) measurement of internal and external diameters, wall thicknesses and lengths and (2) determination of as-extruded surface finishes. These measurements allowed calculation of circularity (ovality), concentricity and straightness.

As-Extruded Tubes. Early in the first series of extrusion trials one of the tubes (No. 2) was sawed into 12-inch (30.5 cm) long sections (see Figure 22) and numerous ID and OD measurements made. Of particular concern, since extrusion to print dimensions was being attempted, was the circularity and diameter of the ID. The measurement data given in Table 5 indicate that the ID was within the size range [2.380 ± 0.010 inch (6.045 ± 0.025 cm)] desired for the final product. The circularity varied from 0.001 to 0.003 inch (0.003 to 0.008-cm). Again, within the desired tolerance range.

Although the plan was to machine the exterior configuration to obtain the desired concentricity [0.015-inch (0.038-cm)], it was desired to obtain concentricities of this value or better. The data indicate that the highest value was 0.012-inch (0.030-cm) with the majority in the range of 0.005 to 0.009-inch (0.013 to 0.023-cm).

Similar data for the tube extrusions from which torsion tube springs were machined are given in Table 6. Because of the difficulties associated with measuring the internal dimensions accurately, only exterior dimensions were measured. The circularity of the OD's was quite good ranging from 0.002 to 0.006-inch (0.005 to 0.015-cm).

As the data in Table 6 and a photograph (Figure 23) of the as-extruded tubes indicate, the first 2 feet (0.6-meter) of the nose portion was bowed. The straightness ranging from 0.6 to 0.9 inches per foot (5.0 to 7.4 cm per m). The remainder of the as-extruded tubes came near to meeting the desired final product straightness of 0.02 inches per foot (0.17 cm per m).

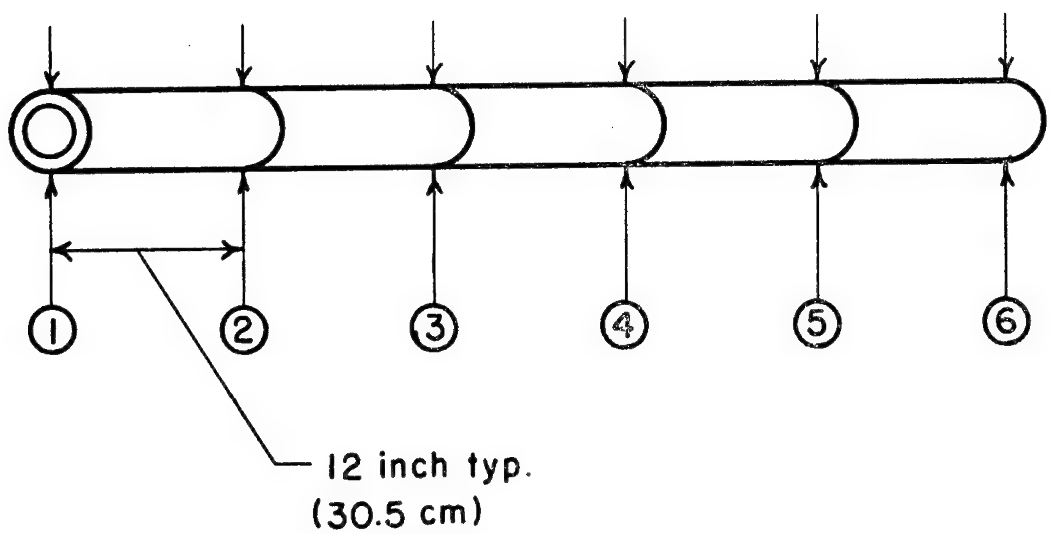


FIGURE 22. LOCATION OF MEASUREMENT STATIONS OF TORSION TUBE EXTRUSION NO. 2

TABLE 5. DIMENSIONS OF TORSION TUBE BLANK NO. 2
Note: Refer to Figure 22 for locations at which the dimensions were obtained.

	Tube Axis, degrees	Dimensions at Station Number, inch (cm)					
		1	2(1)	3	4	5	6
OD	0	3.270 (8.306)	3.242 (8.235)	3.241 (8.232)	3.243 (8.237)	3.242 (8.235)	3.241 (8.232)
	90	3.268 (8.301)	3.240 (8.230)	3.241 (8.232)	3.241 (8.232)	8.242 (8.235)	3.241 (8.232)
ID	0	2.106 (5.349)	2.340 (5.944)	2.377 (6.038)	2.380 (6.045)	2.380 (6.045)	2.380 (6.045)
	90	2.106 (5.349)	2.340 (5.944)	2.375 (6.033)	2.378 (6.040)	2.379 (6.043)	2.377 (6.038)
Wall Thickness	0	0.575 (1.461)	0.447 (1.135)	0.432 (1.097)	0.435 (1.105)	0.428 (1.087)	0.441 (1.120)
	90	0.575 (1.461)	0.450 (1.143)	0.430 (1.092)	0.430 (1.092)	0.439 (1.115)	0.429 (1.090)
	180	0.583 (1.481)	0.445 (1.130)	0.433 (1.100)	0.429 (1.090)	0.434 (1.102)	0.423 (1.074)
	270	0.584 (1.483)	0.441 (1.120)	0.435 (1.105)	0.433 (1.100)	0.425 (1.080)	0.431 (1.095)
Circularity(2), OD		0.002 (0.005)	0.002 (0.005)	0.000 (0.00)	0.002 (0.005)	0.000 (0.00)	0.000 (0.00)
ID		0.000 (0.000)	0.000 (0.00)	0.002 (0.005)	0.002 (0.005)	0.001 (0.003)	0.003 (0.008)
Concentricity(3)		0.009 (0.023)	0.009 (0.023)	0.005 (0.013)	0.005 (0.013)	0.011 (0.028)	0.012 (0.030)

(1) Measurements in this area are in transition zone from small tube ID to large tube ID
(2) Circularity = $D_{max} - D_{min}$
(3) Concentricity = $t_{max} - t_{min}$

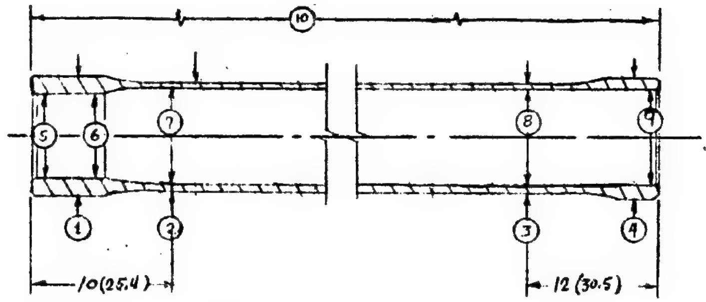


TABLE 6. DIMENSIONS OF MACHINED TUBES

Tube Number	Station / Tube Axis, degrees	1 (0)	1 (90)	2 (0)	2 (90)	3 (0)	3 (90)	4 (0)	4 (90)	5 (0)	5 (90)	6 (0)	6 (90)	7 (0)	7 (90)	8 (0)	8 (90)	9 (0)	9 (90)	10
		Dimensions, Inches (cm)																		
7		3.000 (7.620)	3.000 (7.620)	2.703 (6.866)	2.703 (6.866)	27.00 (6.858)	2.700 (6.585)	3.000 (7.620)	3.000 (7.620)	2.186 (5.552)	2.162 (5.491)	2.355 (5.982)	2.358 (5.989)	2.370 (6.020)	2.400 (6;096)	2.387 (6.063)	2.387 (6.063)	2.388 (6.066)	2.391 (6.073)	75.050 (190.63)
8		2.998 (7.615)	2.998 (7.615)	2.702 (6.863)	2.701 (6.861)	2.700 (6.858)	2.700 (6.585)	2.999 (7.617)	3.000 (7.620)	2.155 (5.474)	2.166 (5.502)	3.155 (5.474)	2.162 (5.491)	2.355 (5.982)	2.400 (6.096)	2.385 (6.058)	2.397 (6.081)	2.388 (6.066)	2.390 (6.071)	75.030 (190.58)
10		2.999 (7.617)	2.999 (7.617)	2.704 (6.868)	2.705 (6.871)	2.700 (6.858)	2.701 (6.861)	3.000 (7.620)	3.002 (7.625)	2.153 (5.469)	2.153 (5.469)	2.154 (5.476)	2.153 (5.476)	2.352 (5.974)	2.356 (5.984)	2.387 (6.063)	2.389 (6.068)	2.389 (6.068)	2.388 (6.066)	75.010 (190.53)
12		2.999 (7.617)	2.999 (7.617)	2.705 (6.871)	2.704 (6.868)	2.701 (6.861)	2.701 (6.861)	2.999 (7.617)	2.999 (7.617)	2.157 (5.497)	2.156 (5.476)	2.156 (5.476)	2.156 (5.476)	2.353 (5.977)	2.348 (5.964)	2.386 (6.060)	2.390 (6.071)	2.386 (6.060)	2.386 (6.060)	75.030 (190.58)
13		3.001 (7.623)	3.001 (7.623)	2.701 (6.861)	2.701 (6.861)	2.701 (6.861)	2.701 (6.861)	3.001 (7.623)	3.000 (7.620)	2.155 (5.474)	2.155 (5.474)	2.156 (5.476)	2.156 (5.476)	2.382 (6.050)	2.366 (6.010)	2.385 (6.058)	2.385 (6.058)	2.387 (6.063)	2.384 (6.063)	75.030 (190.53)
Desired		3.000-0.005 (7.620-0.013)		2.700* Nom. (6.858)		2.700* Nom. (6.858)		2.150 + 0.005 (7.620-0.013)		2.150 + 0.005 (5.461 + 0.013)		(5.461 + 0.013)		(6.045)		(6.045)		(6.045)		(190.5 ± 0.32)

* Maintain wall thickness 0.160 ± 0.010 inch (0.406 ± 0.25 cm).

FIGURE 23. AS-EXTRUDED 4340 STEEL TORSION TUBE BLANKS FORMED IN SECOND SERIES OF TRIALS

Examination of a longitudinal tube section containing the transition zone indicated that the angle transition on the mandrel had formed a curved transition in the extruded blank. Measurement of this transition zone (see Figure 24) indicated that the 20-degree transition on the mandrel had formed a 4.35-inch (11.1-cm) radius transition. Increasing the angle on the mandrel the appropriate amount should provide the desired 3.5-inch (8.9-cm) radius in this transition zone. This capability would delete the need to finish machine this region.

Straightened Tubes. With the exception of straightness, the dimensions of all 7 tubes extruded during the second series of trials appeared to be satisfactory for machining to the final torsion tube spring configuration (Figure 24). Thus, three point bending was used to warm straighten the seven tubes.

After straightening, the external dimensions and maximum bow were rechecked. These data are given in Table 7. Previously, the data had indicated a close relationship between the ovality of the internal and external diameters of as-extruded tubes. Note that the circularity after straightening has increased from a nominal 0.003 to 0.004-inch (0.008 to 0.010-cm) to 0.019 to 0.054-inch (0.048 to 0.137-cm).

The straightness data given in Table 7 are after warm straightening. A small amount of additional cold straightening, in three point bending, was accomplished to obtain the required straightness of 0.02 inches per foot (0.17 cm per m).

Machining of Torsion Tube Springs

The machining of the HYDRAFILM extruded 4340 steel torsion tube to the configuration defined by Ordnance Corps Drawing No. DTA163468 with Rev. A dated December 2, 1971, (see Figure 1) was accomplished in two stages. All exterior and interior lathe machining was accomplished at Battelle's Columbus Laboratories (BCL). The

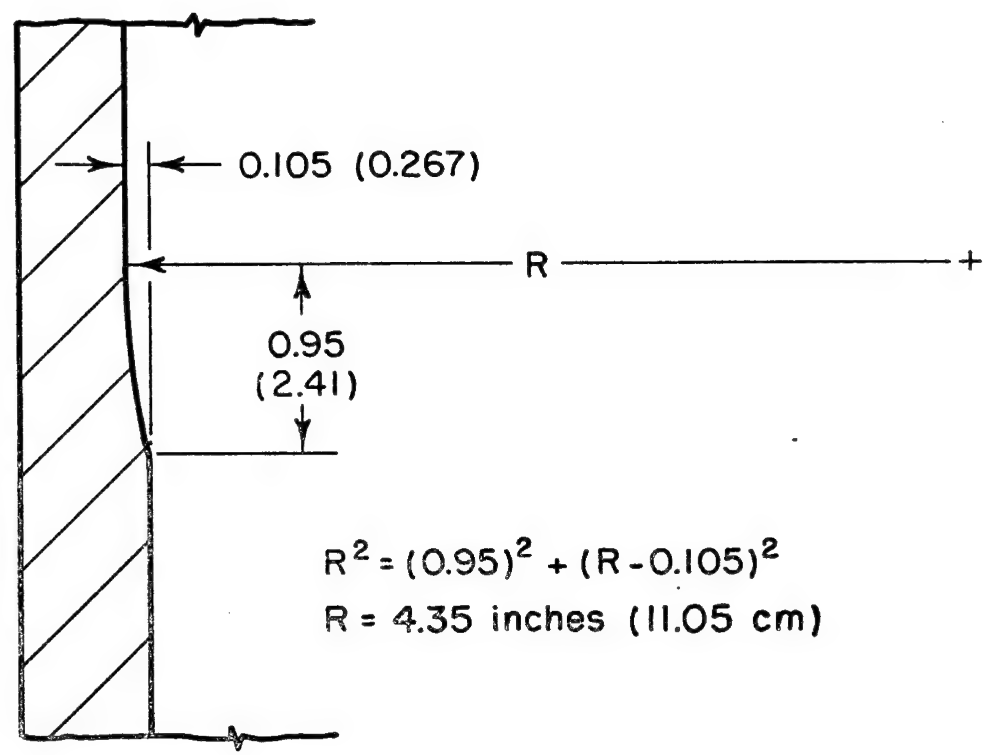


FIGURE 24. CONFIGURATION OF TRANSITION REGION IN AS-EXTRUDED 4340 STEEL TORSION TUBE BLANKS

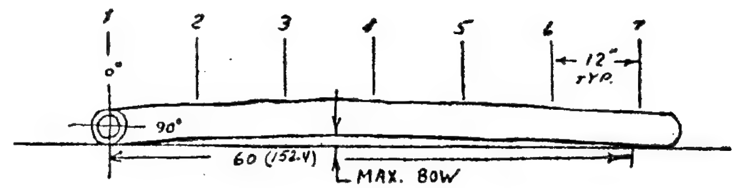


TABLE 7. TORSION TUBE BLANK MEASUREMENTS TAKEN AFTER WARM STRAIGHTENING

Extrusion Number	Tube Axis, degrees	OD Measurements at Station Number, Inches (cm) 1	2	3	4	5	6	7	Straightness in/ft. (cm/m)	Circularity Inches (cm) Maximum	Mean	Standard Deviation
7	0	3.166 (8.042)	3.159 (8.024)	3.140 (7.976)	3.132 (7.955)	3.143 (7.983)	3.138 (7.971)	3.135 (7.963)	0.04 (0.35)	0.041 (0.104)	0.016 (0.041)	0.015 (0.038)
	45	--	3.118 (7.920)	--	3.124 (7.935)	--	3.143 (7.983)	--				
	90	3.162 (8.031)	3.120 (7.925)	3.131 (7.953)	3.109 (7.897)	3.131 (7.953)	3.130 (7.950)	3.138 (7.971)				
	135	--	3.157 (8.019)	--	3.141 (7.978)	--	3.139 (7.973)	--				
8	0	3.163 (8.034)	3.131 (7.953)	3.131 (7.453)	3.136 (7.965)	3.139 (7.973)	3.117 (7.917)	3.128 (7.945)	0.011 (0.09)	0.050 (0.127)	0.025 (0.064)	0.016 (0.041)
	45	--	3.150 (8.001)	--	3.142 (7.981)	--	3.137 (6.968)	--				
	90	3.143 (7.983)	3.004 (7.834)	3.123 (7.932)	3.142 (7.981)	3.119 (7.922)	3.129 (7.943)	3.134 (7.960)				
	135	--	3.100 (7.874)	--	3.107 (7.892)	--	3.101 (7.877)	--				
9	0	3.154 (8.011)	3.135 (7.963)	3.129 (7.948)	3.143 (7.983)	3.137 (7.968)	3.154 (8.001)	3.140 (7.976)	0.03 (0.22)	0.054 (0.137)	0.024 (0.061)	0.016 (0.041)
	45	--	3.150 (8.001)	--	3.142 (7.981)	--	3.137 (7.968)	--				
	90	3.141 (7.978)	3.122 (7.930)	3.124 (7.935)	3.104 (7.884)	3.119 (7.922)	3.100 (7.874)	3.123 (7.932)				
	135	--	3.117 (7.917)	3.127 (7.943)	3.115 (7.912)	3.130 (7.950)	3.116 (7.915)	--				
10	0	3.150 (8.001)	3.120 (7.925)	3.125 (7.938)	3.128 (7.945)	3.123 (7.932)	3.107 (7.892)	3.126 (7.940)	0.01 (0.08)	0.040 (0.102)	0.016 (0.041)	0.016 (0.041)
	45	--	3.113 (7.907)	--	3.102 (7.879)	--	3.118 (7.920)	--				
	90	3.146 (7.991)	3.116 (7.915)	3.131 (7.953)	3.114 (7.910)	3.129 (7.948)	3.147 (7.993)	3.123 (7.955)				
	135	--	3.125 (7.938)	--	3.139 (7.973)	--	3.124 (7.935)	--				
11	0	3.141 (7.978)	3.115 (7.912)	3.124 (7.935)	3.119 (7.922)	3.124 (7.935)	3.125 (7.938)	3.124 (7.935)	0.04 (0.35)	0.029 (0.074)	0.013 (0.033)	0.009 (0.023)
	45	--	3.109 (7.897)	--	3.109 (7.897)	--	3.128 (7.945)	--				
	90	3.152 (8.006)	3.133 (7.958)	3.129 (7.948)	3.123 (7.932)	3.130 (7.950)	3.126 (7.940)	3.132 (9.955)				
	135	--	3.138 (7.971)	--	3.131 (7.953)	--	3.121 (7.927)	--				
12	0	3.151 (8.004)	3.126 (7.940)	3.125 (7.938)	3.127 (7.943)	3.131 (7.953)	3.123 (7.932)	3.123 (7.932)	0.01 (0.01)	0.041 (0.104)	0.023 (0.058)	0.019 (0.048)
	45	--	3.132 (7.955)	--	3.099 (7.871)	--	3.097 (7.866)	--				
	90	3.129 (7.948)	3.113 (7.907)	3.127 (7.943)	3.113 (7.907)	3.119 (7.922)	3.125 (7.938)	3.129 (7.948)				
	135	--	3.106 (7.889)	--	3.140 (7.976)	--	3.150 (8.001)	--				
13	0	3.147 (7.993)	3.131 (7.953)	3.129 (7.948)	3.121 (7.927)	3.131 (7.953)	3.115 (7.912)	3.124 (7.935)	0.01 (0.10)	0.019 (0.048)	0.010 (0.025)	0.007 (0.018)
	45	--	3.124 (7.935)	--	3.130 (7.950)	--	3.116 (7.915)	--				
	90	3.127 (7.943)	3.122 (7.930)	3.128 (7.945)	3.118 (7.920	3.123 (7.932)	3.126 (7.940)	3.127 (7.943)				
	135	--	3.130 (7.950)	--	3.111 (7.902)	--	3.105 (7.887)	--				

partially finished torsion tube springs were then shipped to Machine Products Company, Incorporated, LaCrosse, Wisconsin, for machining of the internal and external splines, heat treatment and shot peening. Only those machining operations accomplished at BCL will be discussed since Machine Products Company, Incorporated, would not disclose their proprietary methods used for the splining and heat treatment.

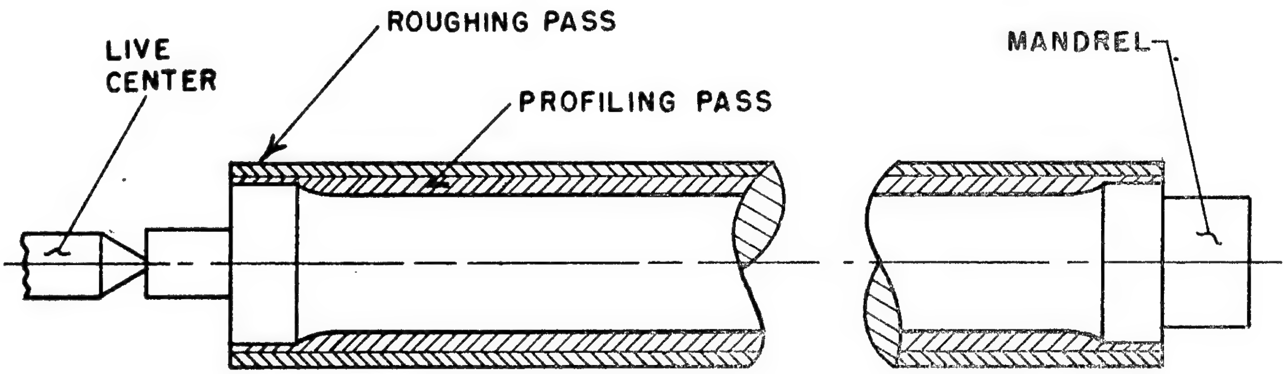
Machining Operations

As already mentioned, dimensional evaluation of the straightened tube blanks revealed that the ovality (circularity) was not as good as that obtained in the as-extruded products. Consequently, the ID of all tubes were honed to meet the circularity and surface finish requirements for the torsion tube springs.

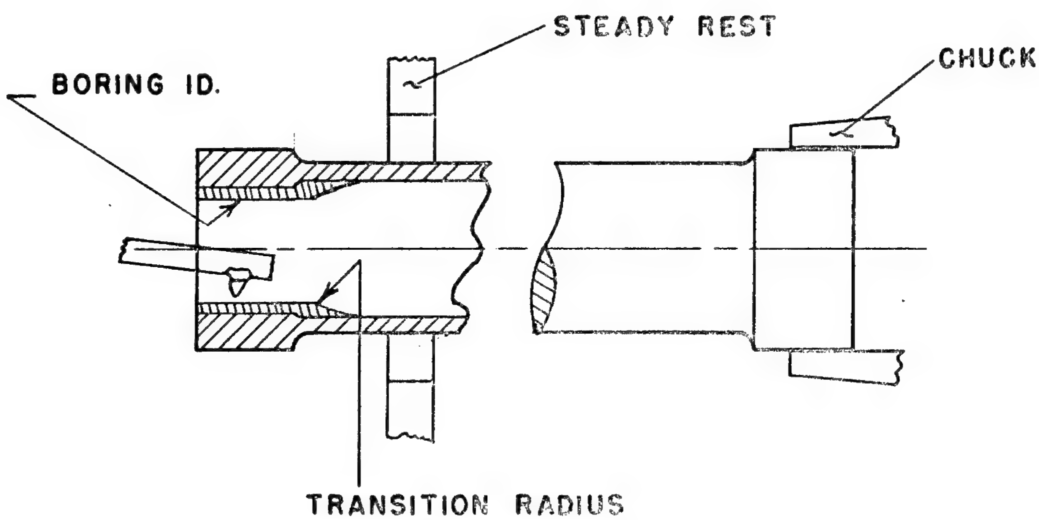
After honing, the torsion tube blanks were mounted onto a closely fitting mandrel and chucked in a LeBlond Gap type engine lathe. This fixturing provided machining of the OD to the ID centerline. A hydraulically actuated tracer attachment (Tymac Model 300) was used to machine the exterior configuration and the radius of the ID transition. The sequence of machining operations included:

(1) Machine external profile (see Figure 25a)
 (a) Roughing pass
 (b) Rough machine profile with tracer attachment
 (c) Finish machine profile with tracer attachment
(2) Bore small internal diameter (see Figure 25b)
(3) Machine transition radius with tracer attachment
(4) Face both ends to length.

A general purpose (V. R. Wesson No. 75) carbide insert was used for all operations at a speed of 200 to 250 surface feet per minute (61.0 to 76.2 surface meters per minute).



a. Machining External Profile



b. Machining Internal Profile

FIGURE 25. MACHINING OF EXTERNAL AND INTERNAL PROFILES

Dimensions of Machined Tubes

During machining, it was determined that the small internal diameter would be oversize on two of the seven extruded blanks. Thus, only five torsion tube springs were completely machined. Their dimensions are given in Table 8. The small internal diameter of one of the tubes (No. 7) did not completely clean-up to the desired diameter. Thus, the internal splines on this tube will not be deep enough. The other significant measurements are the wall thickness variation and concentricity. These data are summarized in Table 9. Two of the five torsion tubes have a wall thickness variation within the desired tolerance range [± 0.010-inch (± 0.025 cm)], one is very close to the range (No. 8) and the other two are on the plus side by 0.006 to 0.008-inch (0.015 to 0.020-cm). Decreasing the outside diameter of the center section by this amount would have brought them into the desired tolerance range. In only one case (Tube No. 8) does the concentricity significantly exceed that desired [0.015-inch (0.038-cm)] and this could result from a difference in the method used to calculate the concentricity.

Summary of Fabrication Results

The results of the warm HYDRAFILM extrusion trials demonstrated

(1) The potential to extrude 4340 tubes at reduction ratios as high as 25:1 with extrusion pressures of 200,000 psi (1379 MPa) and a billet temperature of 1550 F (843 C).

(2) The ability to obtain as-extruded surface finishes in the range of 60 to 100 microinches (1.52 to 2.54 μm) on both internal and external surfaces.

(3) The ability to obtain as-extruded concentricities of 0.005 to 0.012-inch (.013 to .030 cm) and circularities of 0.001 to 0.003-inch (.003 to .008 cm).

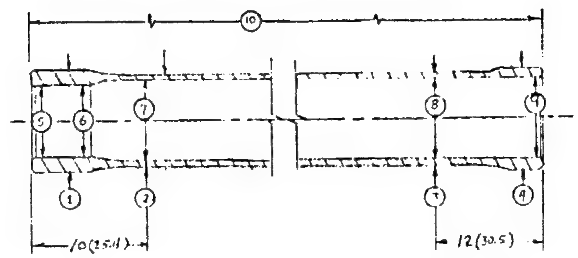


TABLE 8. DIMENSIONS OF MACHINED TUBES

Tube Number	Station / Tube Axis, degrees	Dimensions, Inches (cm)																	
		1		2		3		4		5		6		7		8		9		10
		0	90	.0	90	0	90	0	90	0	90	0	90	0	90	0	90	0	90	
7		3.000 (7.620)	3.000 (7.620)	2.703 (6.866)	2.703 (6.866)	27.00 (6.858)	2.700 (6.585)	3.000 (7.620)	3.000 (7.620)	2.186 (5.552)	2.162 (5.491)	2.355 (5.932)	2.358 (5.989)	2.370 (6.020)	2.400 (6;096)	2.387 (6.063)	2.387 (6.063)	2.388 (6.066)	2.391 (6.073)	75.050 (190.63)
8		2.998 (7.615)	2.998 (7.615)	2.702 (6.863)	2.701 (6.861)	2.700 (6.858)	2.700 (6.585)	2.999 (7.617)	3.000 (7.620)	2.155 (5.474)	2.166 (5.502)	3.155 (5.474)	2.162 (5.491)	2.355 (5.932)	2.400 (6.096)	2.385 (6.058)	2.397 (6.081)	2.388 (6.066)	2.390 (6.071)	75.030 (190.58)
10		2.999 (7.617)	2.999 (7.617)	2.704 (6.868)	2.705 (6.871)	2.700 (6.858)	2.701 (6.861)	3.000 (7.620)	3.002 (7.625)	2.153 (5.469)	2.153 (5.469)	2.154 (5.476)	2.153 (5.476)	2.352 (5.974)	2.356 (5.984)	2.387 (6.063)	2.389 (6.068)	2.389 (6.068)	2.388 (6.066)	75.010 (190.53)
12		2.999 (7.617)	2.999 (7.617)	2.705 (6.871)	2.704 (6.868)	2.701 (6.861)	2.701 (6.861)	2.999 (7.617)	2.999 (7.617)	2.157 (5.497)	2.156 (5.476)	2.156 (5.476)	2.156 (5.476)	2.353 (5.977)	2.348 (5.964)	2.386 (6.060)	2.390 (6.071)	2.386 (6.060)	2.386 (6.060)	75.030 (190.58)
13		3.001 (7.623)	3.001 (7.623)	2.701 (6.861)	2.701 (6.861)	2.701 (6.861)	2.701 (6.861)	3.001 (7.623)	3.000 (7.620)	2.155 (5.474)	2.155 (5.474)	2.156 (5.476)	2.156 (5.476)	2.382 (6.050)	2.366 (6.010)	2.385 (6.058)	2.385 (6.058)	2.387 (6.063)	2.384 (6.063)	75.030 (190.58)
Desired		3.000-0.005 (7.620-0.013)		2.700* Nom. (6.858)		2.700* Nom. (6.858)		2.150 + 0.005 (7.620-0.013)		2.150 + 0.005 (5.461 + 0.013)		(5.461 + 0.013)		(6.045)		(6.045)		(6.045)		(190.5 ± 0.32

* Maintain wall thickness 0.160 ± 0.010 inch (0.406 ± 0.25 cm).

TABLE 9. SUMMARY OF SIGNIFICANT DIMENSIONAL DATA

Torsion Tube Number	Wall Thickness Variation(1), in. (cm)	Concentricity(2), in. (cm)
7	+ 0.007 (0.018) - 0.008 (0.020)	0.002 to 0.016 (0.005 to 0.041)
8	+ 0.014 (0.036) - 0.009 (0.023)	0.004 to 0.023 (0.010 to 0.058)
10	+ 0.016 (0.041) - 0.008 (0.020)	0.002 (0.005)
12	+ 0.018 (0.046) - 0.006 (0.015)	0.001 to 0.004 (0.003 to 0.010)
13	+ 0.008 (0.020) - 0.002 (0.005)	0.008 (0.020)
Desired	± 0.010 (0.025)	0.015(3) (0.038)

(1) Variation in wall thickness from desired 0.160-inch (0.406-cm)
(2) Concentricity = $t_{max} - t_{min}$
(3) Calculation technique not stated.

(4) The potential for forming the transition radius during the primary extrusion operation.

(5) The ability to separate the extruded product from the extrusion butt as part of the extrusion cycle. This in turn demonstrates the feasibility of applying TMP (thermomechanical processing), which requires quenching immediately after the forming operation, to the fabrication of torsion tube springs.

(6) The reproducibility of the process -- variation in extrusion pressure was only ± 4000 psi (± 27.6 MPa).

With the present tooling design and procedures, the straightness of the as-extruded tubes does not meet the requirements for the finished part configuration. There are two approaches to this problem -- use of a conventional roll straightener or modifying the tooling design to include a straightening die. The capabilities of conventional roll straighteners are known; the effectiveness of a straightening die would have to be determined. However, if TMP is contemplated, a roll straightener could not do the job. The extrusion should be as straight as possible before oil quenching and addition of a straightening die would be the most logical approach for improving straightness.

COST ANALYSIS

The objectives of this part of the program were to estimate the costs for fabricating torsion tube springs by use of the warm HYDRAFILM extrusion process. The steps involved in this effort included (1) definition of the production sequence and operations, (2) generation of data and equations for estimating production costs, (3) calculation of estimated costs for production at several quantity levels and (4) comparison of estimated production costs for the HYDRAFILM process and machining from drawn 4340 steel tubing.

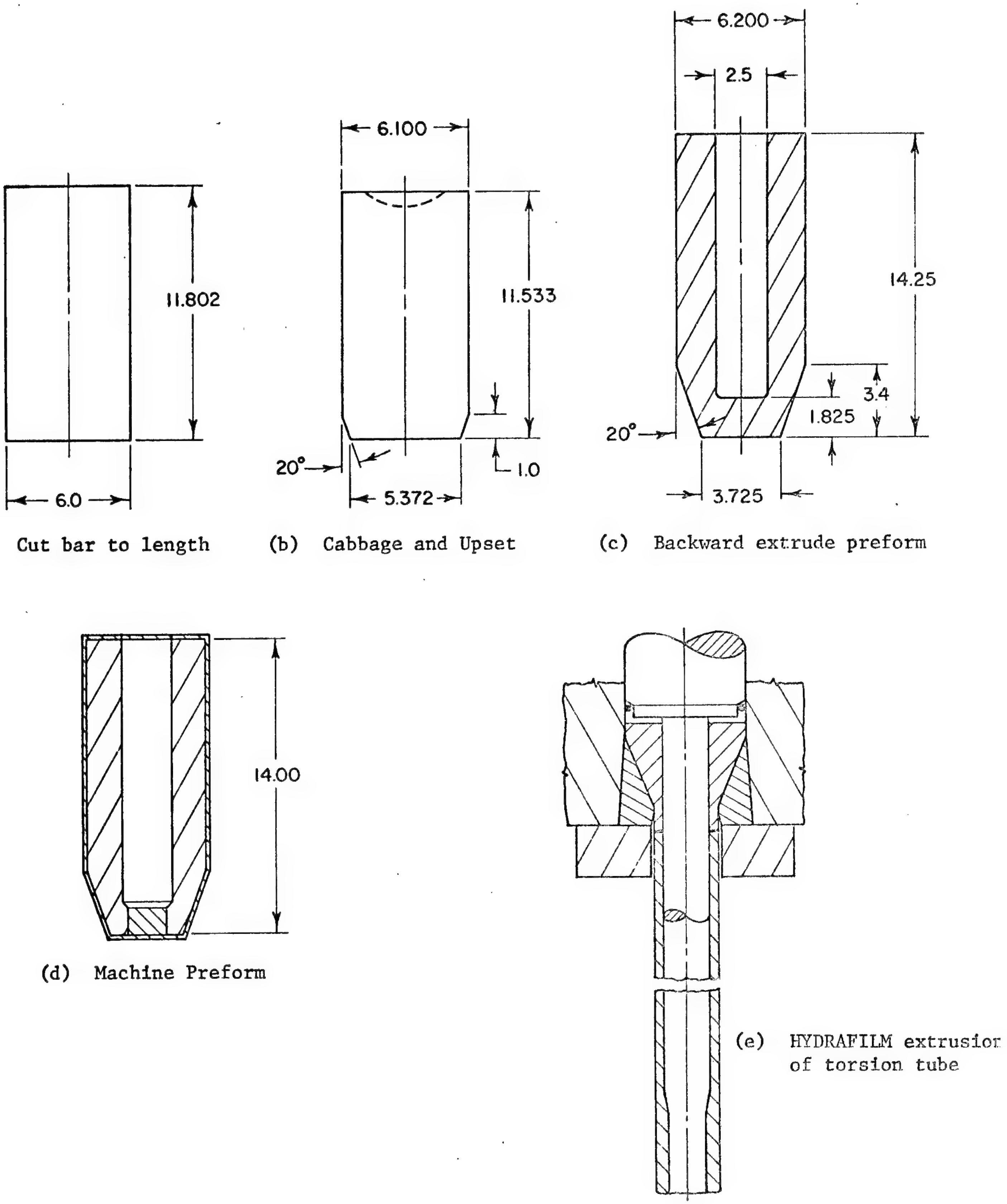
The costs estimated as a result of this analysis are based on a set of defined assumptions and calculated using established analytical techniques[5,6]. These costs are not based on production experience. Therefore, their accuracy is not known. Based on similar work done on other programs, it is reasonable to assume an accuracy of at least 20 percent.

Definition of Production Sequence

The sequence of operations needed to go from as-received aircraft quality 4340 steel bar stock to a ready to machine torsion tube blank is shown in Figure 25. The as-received bar is sawed to length and forged to the configuration shown in Figure 25b. A combination of backward cup and forward extrusion is then used to warm form the preform for the HYDRAFILM extrusion operation. Machining to the preform dimensions used for this program would involve the operations shown in Figure 26. It is assumed that the ID would be used in the as-formed condition. If a concentricity of 0.005 to 0.010-inch (0.013 to 0.025-cm) can be maintained in the warm formed preform, the results of the extrusion trials indicate that it may be possible to delete machining operations 1, 2 and 5. In either case, all machined surfaces would be referenced to the as-formed ID. This would be accomplished by mounting the preform on a closely-fitting mandrel.

The production method assumed for application of water-base graphite lubricants is illustrated in Figure 27. The machined preform would be loaded onto the belt of a continuous feed furnace, heated to approximately 300 F (149 C), and then sprayed using an apparatus similar to that depicted in the figure.

The remainder of the forming sequence includes heating the preform to extrusion temperature [1550 F (843 C] and HYDRAFILM extrusion of the torsion tube blanks.



(a) Cut bar to length

(b) Cabbage and Upset

(c) Backward extrude preform

(d) Machine Preform

(e) HYDRAFILM extrusion of torsion tube

FIGURE 26. SEQUENCE OF OPERATIONS FOR FORMING TORSION TUBE BLANKS

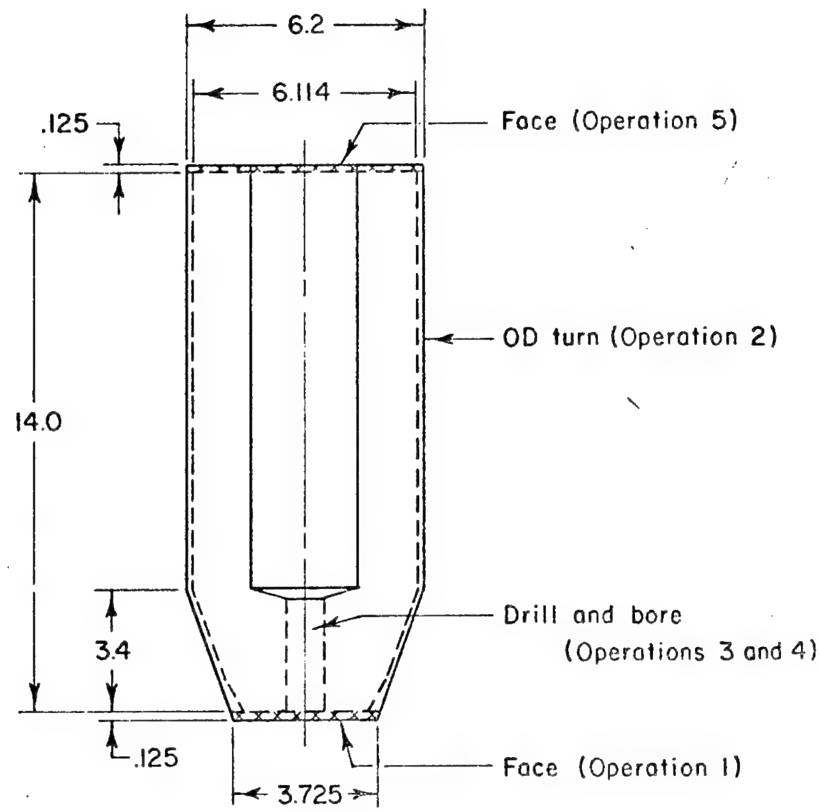


FIGURE 27. MACHINING OPERATIONS FOR HYDRAFILM EXTRUSION PREFORM

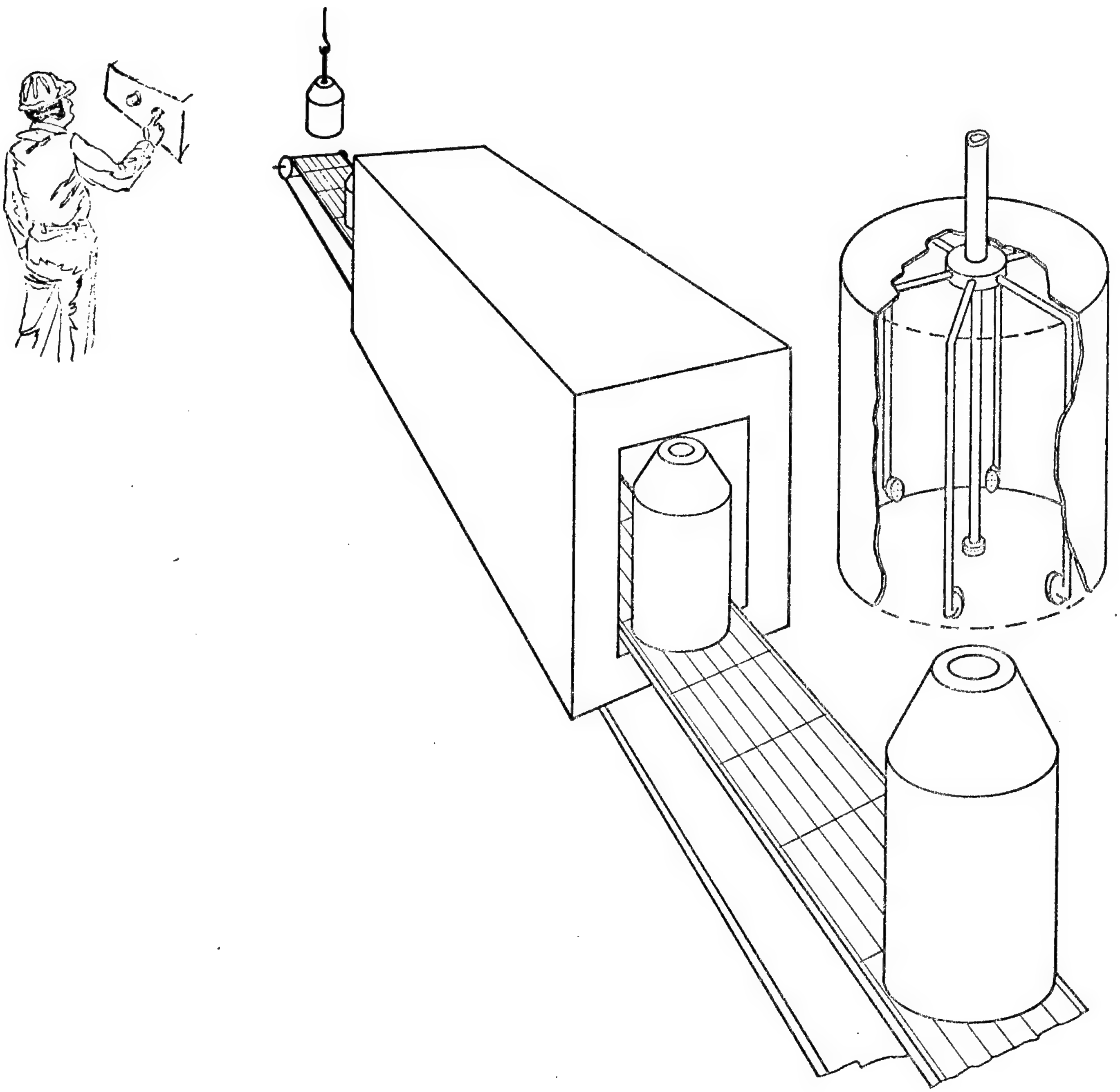


FIGURE 28. APPLICATION OF WATER-BASE GRAPHITE LUBRICANTS TO HYDRAFILM EXTRUSION PREFORM

Cost Equations

The equations used for estimating production costs were generated using either historical data (quotations, etc.), standard machining equations or assumptions pertaining to production rate capabilities, manpower requirements, etc. The costs for accomplishing machining operations were all estimated by use of machining equations and machinability data available in the open literature.

Machining Cost Equations

All machining costs were estimated using the basic equations and data contained in References (5) and (6). The general procedure followed when utilizing these equations was:

(1) Analyze the part to determine the machining operations required

(2) Determine the sequence of operations and number of set-ups required

(3) Calculate standard times of each operation using established equations.

This procedure was then applied to (1) billet preparation operations, (2) extrusion preform machining, and (3) machining of final part configuration.

Billet Preparation. This operation involves the use of a circular metal cutting saw to cut the incoming 6-inch (15.2-cm) diameter rods into 11.8-inch (30-cm) lengths. The assumptions made concerning this operation are:

(1) Thirteen cuts, each 1/8-inch (.003-cm) wide, will be required to obtain 12 billets from each 12-foot (3.7-m) long bar

(2) The 4340 steel bar can be cut at a rate of 51.43 square inches per minute (331.8 cm^2 per min)

(3) Each saw blade may be resharpened 10 times before replacement is necessary

(4) 12,000 square inches of billet can be cut before resharpening is necessary.

Equipment amortization costs were not included. The cost equation has the form

$$C_{SAWB} = t_L L_1 + C_{TOOL} \tag{11}$$

where

t_L = labor hours required per billet

L_1 = labor rate, dollars per hour

C_{TOOL} = expendable tooling cost per billet

The labor hours include productive (actual sawing) and non-productive (loading, unloading, etc.) time. When an automatic feeding system is coupled to the saw, the non-productive time per billet becomes about 2 minutes (.033 hr)*. The calculation for labor hours then becomes

$$t_L = \frac{\pi D^2 \ (1.08) \ (.017)}{4 \ (51.43)} + 0.033 \tag{12}$$

where

D = bar diameter

1.08 = factor to account for 13 cuts per 12 billets

0.017 = conversion factor - minutes to hours

The expendable tooling cost may be calculated in a similar manner

$$C_{TOOL} = \frac{(1.08) \ \pi \ D^2}{4 \ (12,000)} \ [250 + (10) \ (100)] \tag{13}$$

Contact with a local machine tool supplier indicated an initial cost of about \$250. per blade plus \$100. for each resharpening.

Combining these equations gives

$$C_{SAW} = (0.043) \ L_2 + 0.318 \tag{14}$$

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*Data obtained by observation of automatic circular saw in operation at Babcock and Wilcox Co., Beaver Falls, Pennsylvania.

Preform Machining. The dimensional data given in Figure 26 were used to calculate the volume of material to be removed in each operation. The assumed sequence of operations is:

(1) Setup 1
   (a) Face nose (operation 1)
   (b) Machine OD (operation 2)
   (c) Drill (operation 3)
   (d) Bore (operation 4)
(2) Setup 2
   (a) Face butt (operation 5).

The machining costs equations have the form

$$C_{MACH} = t_{RUN}L_1 + t_{SETUP}L_1 + C_{TOOL} \quad (15)$$

Run and setup costs were calculated using the equations and methods given in Reference (5). All expendable tooling costs for the turning operations are based on the use of throwaway carbide inserts and a tool life of 1 hour. The calculated preform machining cost is

$$C_{P\ MACH} = 0.541\ L_1 + \frac{8.458L_1}{Q} + 2.16 \quad (16)$$

where Q = number of parts machined per setup.

Pusher Block Machining. The separation of the extruded product (torsion tube blank) from the extrusion butt during the extrusion cycle requires the use of a pusher block. The dimensions of this block are: 6.0-inch (15.2-cm) OD x 2.50-inch (6.35-cm) ID x 2.4-inch (6.1-cm) long. The fabrication of this piece would include

(1) Saw cut from as-received 6-inch (15.2-cm) diameter 4340 steel rod
(2) Face both ends
(3) Drill 2.5-inch (6.35-cm) hole.

The cost equation for these operations was generated in the same way as for saw cutting the billet and machining the preform. This equation is

$$C_{PB\ MACH} = 0.027L_2 + 0.115\ L_1 + \frac{2.117\ L_1}{Q} + 0.79 \qquad (17)$$

where

L_1 = rate for skilled labor
L_2 = rate for semi-skilled labor
Q = number of parts machined per setup

Machining of Torsion Tube Blanks. The results of the Phase II experimental effort indicate

(1) The internal diameters can be extruded to the tolerances needed.
(2) The surface finish of the ID [80 to 100 microinches (1.5 to 2.5 μm)] exceeds the product requirements. Thus honing of the major internal diameter will be necessary.
(3) The internal transition between diameters may be formed during the extrusion operation.
(4) Circularity of the as-extruded torsion tube blank will meet the part requirements. When the blanks are warm straightened, care must be used to prevent degradation.

Based on the above, the processing sequence assumed for the cost analysis includes

(1) Saw cut extrusion to 75 + 1/4-inch (190.5 + 0.6 cm)
(2) External machining (blank mounted on close-fitting mandrel)
(3) Bore minor internal diameter
(4) Face to length
(5) Hone major internal diameter
(6) Broach splines.

Saw Cut Extrusion. The assumptions previously made for circular saw cutting of the forging billets to length are also applicable to these operations. In this case, however, there are two cuts per torsion tube blank. An automatic feed device probably could not be used for this operation. Thus, additional labor time must be included for set-up. The cost equation used for this operation is:

$$C_{SAWE} = 0.078\ L_2 + 0.102 \tag{18}$$

Lathe Turning Operations. To attain the required ± 0.010-inch (± 0.025-cm) tolerance in wall thickness, it is necessary to rigidly support the torsion tube blank on a mandrel. If the quantity to be produced is small, a solid mandrel would probably be used because of its lower cost. As the quantity produced increases, there would be sufficient justification to use an expanding mandrel. For large quantities the set-up time saved would more than offset the additional fixturing cost. The machining sequence used to generate the cost equation is:

(1) Setup 1 - tube blank on mandrel
  - (a) Rough turn OD to 3.050-inch (7.747-cm)
  - (b) Rough turn center section to 2.750-inch (6.985-cm)
  - (c) Contour turn to 3.000/2.700-inch (7.620/6.858-cm)

(2) Setup 2 - chuck plus steady rest
  - (a) Bore minor internal diameter to 2.150-inch (5.461-cm)
  - (b) Face end to length

(3) Setup 3 - Face to overall length of 75-inch (190.5-cm).

As before, the volume of metal to be removed in each operation is calculated, the metal removal rate determined, and the standard times calculated. The standard times calculated for machining of the 4340 steel torsion tube blanks are given in Table 10. Substituting these times and tooling cost into a cost equation gives

$$C_{MACHE} = 1.145\ L_1 + \frac{4.840\ L_1}{Q} + 4.580 \tag{19}$$

TABLE 10. CALCULATED STANDARD TIMES FOR LATHE MACHINING OPERATIONS

Setup Number	Operation	Standard Times, hrs t_R	t_{SU}
1	Contour turn OD	1.005	1.945
2	Bore and face	0.096	1.930
3	Face	0.044	0.965

Honing of Major Internal Diameter. Although portions of the internal surface can be extruded to a 60 to 80 microinch (1.52 to 2.03 μm) finish, the average surface roughness is much higher [100 to 140 microinches (2.50 to 3.50 μm)]. Thus honing will be needed to obtain the desired 70 microinch (1.75-μm) surface finish. No data which could be used for calculation of standard times was found in the literature. Therefore, an approximate metal removal rate was calculated on the following data (BCL experience).

(1) A 6.25-inch (15.88-cm) internal diameter x 20-inch (50.8-cm) long H-11 tool steel (R_c 52-54) cylinder had its diameter increased by 0.001-inch (0.003-cm) after honing for 1-1/2 hour.

(2) A similar cylinder whose dimensions were 4.75-inch (12.07-cm) ID x 10-inches (25.4-cm) long had its diameter increased by 0.003-inch (0.008-cm) after honing for 1 hour.

By calculation one obtains metal removal rates of 0.0022 to 0.0037 cubic inches per minute. Assuming that a 0.001-inch (.003-cm) increase in tube internal diameter would be necessary to attain the 70 microinch (1.75 μm) finish, approximately 0.27 cubic inches (8.81 cc) of material would have to be removed. The time required to do this would be about 1.5 hours. The amount of nonproductive time should be low for this type of operation and 1 operator could operate more than one machine.

To generate an equation for calculating a cost of honing a torsion tube spring the following assumptions were made:

(1) 1 man would operate 4 machines

(2) The time required for the entire honing operation -- load, hone and unload -- would not exceed 2 hours per part

(3) A set of stones would be capable of honing at least 6 tubes. A set of honing stones, with guides, costs about \$12.00.

The cost equation for this operation then becomes

$$C_{HONE} = \frac{2}{4} L_2 + \frac{12}{6} \tag{20}$$

Broaching of Splines. The data used to generate broaching cost equations was furnished by Apex Broach and Machine Company, Detroit, Michigan[7]. These data (summarized in Table 11) were used to formulate the following cost equations

$$C_{BRCH\ I} = 0.008\ L_2 + \frac{1000}{Q} \tag{21}$$

$$C_{BRCH\ E} = 0.013\ L_2 + \frac{5000}{Q} \tag{22}$$

where

L_2 = rate for semi-skilled labor

Q = 18,000 parts = number of parts produced.

The initial cost of setting up the machine divided by the number of parts made per setup would have to be added to these costs.

Metal Forming Cost Equations

Preform Forging Cost Equation. The cost of producing warm forged preforms was based on quoted fabrication prices[8] for cup-shaped

TABLE 11 SUMMARY OF BROACHING DATA USED TO ESTIMATE COSTS*

	Internal Spline	External Spline
Type of Machine:	15 ton, 36-inch stroke special horizontal	15-ton, 24-inch stoke special vertical
Production Rate Estimate: at 80 percent efficiency	120 parts per hour	80 parts per hour
Tool Life Estimate:	12,000 to 18,000 pieces per grind; 8 to 10 grinds	12,000 to 18,000 pieces per grind; 8 to 10 grinds
Expendable Tooling Cost:	$1,000.00	$7,500.00
Durable Tooling Cost:	$5,000.00	$24,000.00
Capital Equipment Cost:	$58,000.00	$76,000.00

*Data supplied by Apex Broach and Machine Company, Detroit, Michigan

preforms of a similar steel composition. These quotes were modified to reflect the difference in size by using the following ratio (scale factor):

$$S.F. = \frac{\text{Weight of torsion tube preform}}{\text{Weight of cup-shaped preform}} \tag{23}$$

This is a valid assumption because the cost per pound of large as-forged components varies only slightly with component size. In addition, it was assumed that inflation since 1971 had increased cost about 40 percent. The equation used for calculating the preform forging cost is of the form:

$$C_F = (S.F.)\ YQ^{-x} \tag{24}$$

where

Y = cost of producing the first item of any quantity

Q = total number of items produced

x = learning curve factor; normally 0.152 for metal forming operations

For the torsion tube extrusion preform, this equation reduces to

$$C_F = 97.43\ Q^{-0.152} \tag{25}$$

The tooling costs for forging the preform were estimated in a similar manner. The equation used for these estimates is

$$C_T = \frac{2500}{Q} \quad \text{for } Q \leq 500 \tag{26}$$

The quantity Q formed is limited to 500 in anticipation of the punch wear that will be encountered when forming the cavity.

HYDRAFILM Extrusion Cost Equations

Although the feasibility of using warm HYDRAFILM extrusion for the fabrication of torsion tube blanks has been demonstrated, the process has not yet been used in production in the United States. Since historical data for this process is lacking, several assumptions based on production experience with similar metal deformation processes or data from the Phase II experimental extrusion trials were used to generate cost equations. These assumptions are:

(1) A production rate of 20 to 30 parts per hour can be attained with the present tooling design. The average time required to transfer a warm billet from the furnace to the extrusion press and accomplish the extrusion operation during the Phase II trials was 3 minutes.

(2) A conservative die and punch life of 500 parts is assumed.

(3) A three man crew -- press operator, manipulator operator and forge helper -- should be sufficient.

The conversion or forming costs for the HYDRAFILM extrusion operation may be divided into three categories:

(1) Labor costs

(2) Heating and lubrication costs

(3) Expendable tooling costs.

Capital equipment costs were not included as part of the estimated fabrication cost.

Labor Cost. The labor rates will vary depending upon function and responsibility. In this case, it has been assumed that the press operator is the supervisor for the operation and would have a labor rate about 25 percent higher than the helper. The manipulator operator, also in a responsible position, would have a labor rate about 10 percent higher than a helper. If the labor rate of the helper is 1.0, the total

labor rate (all 3 personnel) becomes 3.35. The labor cost per extrusion then becomes

$$C_{LEXT} = \frac{3.35}{R} L_2 \tag{27}$$

where

R = production rate per hour

L_2 = rate for semi-skilled labor.

<u>Heating and Lubrication Costs</u>. The cost to heat the extrusion preform and pusher block to extrusion temperature was estimated by calculating the amount of thermal energy required and multiplying by an average energy cost. Assuming a 50 percent power to heat conversion efficiency, each preform-pusher combination requires about 12 kilowatt hours of electricity. If electricity costs $0.06 per kilowatt hour, the heating cost is $0.72 per extrusion.

The lubrication cost includes (1) the price of lubricants and fluids used and (2) the labor cost associated with their application. Assuming the use of a spray applicator system similar to that shown in Figure 27, the labor costs become quite small. Based on the volume of lubricant used during the Phase II extrusion trials and a lubricant price of $1.25 per pound, the lubricant cost is about $1.75 per extrusion.

<u>Expendable Tooling Costs</u>. The costs for fabricating the required dies, mandrel and miter ring seals are estimated on the basis of the machining times that were required for the Phase II experimental tooling. Assuming a tool shop fabrication cost of $20.00 per hour and a life of 200 parts, the estimated fabrication cost becomes

$$C_{EXTOOL} = \frac{500}{Q} \qquad Q \leq 200 \tag{28}$$

Estimated Production Cost

The developed cost equations were used to estimate the cost to fabricate torsion tube springs at quantity levels of 1000, 5000, 10,000, 20,000, and 30,000 parts. In all instances it was assumed that the total quantity would be a single buy order. The costs were estimated using labor rates of \$18.00 per hour for skilled labor (L_1) and \$14.00 per hour for semi-skilled labor (L_2). These estimated costs are tabulated in Table 12. To the subtotals shown in this table must be added the costs for heat treatment, short peening, non-destructive testing (if required), preservation and packaging.

Cost Comparison

Fabrication of torsion tube springs is currently done by machining from drawn 4340 steel tubing. Earlier in this report (Table 1) an assumed machining sequence was given for this approach. To determine if HYDRAFILM extrusion of torsion tube blanks followed by minimal machining offers any cost advantage over the present method, the fabrication cost for this method was estimated.

Estimated Cost for Machining From Tube

Standard eouations from References (5) and (6) were used to obtain the standard machining times given in Table 13. Substituting this data into a cost equation gives

$$C_{MACHT} = 2.470\ L_1 + \frac{3.875\ L_1}{Q} + 10.833 \qquad (29)$$

The equations used for honing and broaching costs are the same as those used for the extruded torsion tube blank. A summary of the calculated costs are given in Table 14.

TABLE 12 ESTIMATED COSTS TO PRODUCE TORSION TUBE SPRINGS BY HYDRAFILM EXTRUSION

	Estimated Cost per Item Produced, dollars				
Quantity Produced	1000	5000	10,000	20,000	30,000
Preform Cost[1]					
Material Cost[2]	39.50	39.50	39.50	39.50	39.50
Forging Cost	39.10	31.70	29.00	26.60	25.30
Machining Cost	15.30	15.20	15.15	15.15	15.15
HYDRAFILM Extrusion Cost[3]	7.30	7.30	7.30	7.30	7.30
Finish Machining Cost	37.30	32.40	31.80	31.50	31.40
SUBTOTAL	138.50	126.10	122.75	120.35	118.65

(1) Includes cost for pusher block.

(2) Based on 4340 steel cost of $0.323 per pound (material purchased on October 30, 1973).

(3) Assumed production rate of 20 parts per hour; capital equipment costs for extrusion container and support tooling not included

TABLE 13. STANDARD CALCULATED MACHINING TIMES FOR MACHINING TORSION TUBE SPRING FROM DRAWN TUBING

Operation	Standard Times, hrs t_R	t_{su}	Tool Cost,(1) dollars per part
Sawcut to length	0.035	0.034(2)	0.061
Face ends	0.088	1.930	0.352
Gunbore minor ID	0.997	0.083(2)	3.100
Gunbore major ID	0.145	0.083(2)	3.300
Contour Turn OD	1.005	1.945	4.020

(1) Based on use of throway carbide inserts at $4.00 per each and a tool life of 1 hour.
(2) Setup time per part.

TABLE 14. ESTIMATED COSTS TO PRODUCE TORSION TUBE SPRINGS BY MACHINING FROM DRAWN TUBING

Quantity Produced	Estimated Cost per Item Produced, dollars 1000	5000	10,000	20,000	30,000
Material Cost(1)	68.90	68.90	68.90	68.90	68.90
Machining Cost	98.00	93.20	92.60	92.30	92.20
Subtotal	166.90	162.10	161.50	161.20	161.10

(1) Based on aircraft quality 4340 steel drawn tubing at $10.95 per foot. Quotation on August 24, 1974 for 6,000 foot quantity.

Comparison of Costs

Because the assumptions made to calculate the estimated costs impose a degree of inaccuracy, it is more meaningful for comparison purposes to use relative costs based on common assumptions rather than the dollar values predicted. As much as possible, the assumptions made when calculating the estimated costs for each fabrication approach were the same. The methodology used was the same for both methods.

The relative cost for each method was determined by using the estimated cost to machine a torsion tube spring from drawn 4340 steel tubing as the base line. These are listed in Table 15. This comparison predicts a cost saving of at least 17 percent by use of the HYDRAFILM extrusion process.

The material cost for the cold drawn tubing used in the calculations was the price as of August 26, 1974. Delivery was quoted as early 1976 (16 to 18 months delivery) and price would be at time of delivery. The supplier projected a price increase of at least 30 percent. If both bar and drawn tubing prices increase by 30 percent, the process using bar as input material will show an additional savings of up to $12.00 per part.

TABLE 15. RELATIVE COSTS TO PRODUCE TORSION TUBE SPRINGS BY TWO MANUFACTURING SEQUENCES

	Relative Cost per Item Produced				
Quantity Produced	1000	5000	10,000	20,000	30,000
Machining from Drawn Tubing	1.00	1.00	1.00	1.00	1.00
HYDRAFILM Extrusion Process	0.83	0.78	0.76	0.75	0.74

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The objectives of this manufacturing development program were to determine methods capable of producing torsion tubes at reduced manufacturing cost with no sacrifice in quality. The method addressed was HYDRAFILM extrusion of tube blanks and final machining to configuration. It was found that the internal configuration can be brought to a near net condition as extruded, thus precluding much I.D. machining. Failure of the extrusion tooling after 13 trials resulted in the final delivery of only four testable sample items. These were submitted for Government test and evaluation.

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